In presenting the dissertation as a partial fulfillment of the requirements for an advanced degree from the Georgia Institute of Technology, I agree that the Library of the Institute shall make it available for inspection and circulation in accordance with its regulations governing materials of this type. I agree that permission to copy from, or to publish from, this dissertation may be granted by the professor under whose direction it was written, or, in his absence, by the Dean of the Graduate Division when such copying or publication is solely for scholarly purposes and does not involve potential financial gain. It is understood that any copying from, or publication of, this dissertation which involves potential financial gain will not be allowed without written permission.

7/25/68

A DYNAMIC ANALYSIS OF AN ENGINEERING ORGANIZATION

A THESIS

Presented to

The Faculty of the Graduate Division

by

Shinichi Takahashi

In Partial Fulfillment

of the Requirement for the Degree

Master of Science

in the School of Industrial Engineering

Georgia Institute of Technology

August, 1968

A DYNAMIC ANALYSIS OF AN ENGINEERING ORGANIZATION

Approved:

Chairman

Date Approved by Chairman 8/26/68

ACKNOWLEDGMENTS

The author wishes to express his appreciation to Dr. Bobby C. Spradlin, this thesis advisor, for his inspiring friendship, willing advice, and encouragement, not only during all phases of this research, but throughout the entire duration of the author's graduate work at Georgia Institute of Technology. The author also wishes to acknowledge the time and invaluable help given by Dr. Jack R. Walker and Professor Stan Aaronson, the members of the reading committee.

The author extends his appreciation to Mrs. Bobby C. Spradlin and Miss Chieko Shiraishi for their assistance in typing this thesis.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Continued)

SUMMARY

In this study an engineering organization specializing in designing and construction of chemical plants was analyzed by means of a dynamic simulation model. The model was built in accordance with the philosophy and methodology of Industrial Dynamics.

The primary objective of this study was to aid in developing the needed understanding of the real world system dynamics, and secondly it was to provide an opportunity to improve systems behavior under alternate management policy. By using DYNAMO, simulations on a larger-scale digital computer were run to produce the time response of the variables in the model for policy and parameter changes.

The Industrial Dynamics model pointed out some interesting results. Since capable engineers are the greatest asset in an engineering organization, they are the focus of this study. The hypothesized model has demonstrated fluctuations of the engineering know-how level and the work load for engineers which were experienced in an engineering organization. The model also presents fluctuations of the number of orders during the simulation time period of ten years, and hopefully strengthens an understanding of the management problems of an engineering organization.

Since the results indicated that the problems under the original model arose mainly from management policies of the organization controlling the know-how level, a new policy under the improved model was provided to involve a change in the system structure for the feedback of know-how. By adopting the new policy, the recognition of the gap

between the engineering organization's know-how level and the potential know-how level was greatly improved and management created a workable system of much smaller fluctuations of the work load while maintaining a steady increase in the know-how level. This system also proved to be insensitive to variations in the parameter value of management effort influencing the know-how level.

This study suggests the possibility of experiments relating to management policies influencing the total system behavior of an engineering organization.

CHAPTER I

INTRODUCTION

The Second World War gave a tremendous thrust to technological development. New scientific concepts, new products, and new technical needs appeared in bewildering profusion. No longer is it possible for the nation, industry, or firm to be free to choose its own rate of growth and still survive. Pressures created by international and national policies permeated every major policy in industry.

For instance, in Japan, remarkable progress has been made in the rehabilitation and development of the various industries. Especially in the chemical industry, phenomenal developments have been made through the licensing of foreign technical know-how and development of domestic technologies. The fields of the chemical industry covered include the so-called energy industries such as petroleum, coal and natural gas industries, and the popular industries such as petro-chemical, synthetic resin and fiber, and pharmaceutical industries as well as the nuclear industry.

With capital liberalization just ahead, Japanese industries are being urged to improve their competitive position. The chemical industry especially is faced with the necessity to renovate and modernize their existing plants and facilities to overcome international competition.

Under these circumstances, when a new project is undertaken by the chemical industry, whether it is a commercialization of a new domestic development or importation of foreign technical know how, it is common for the industry to consider the services of engineering firms, specializing in plant consultation, designing, construction and test operation in order to construct plants in this technical innovation age.

Most of the engineering firms have adopted the "Project Engineering System" to handle the construction of process plants. This system involves complicated techniques and engineering skills of high standards. Today, plant construction not only requires efficient major equipment but also requires a high standard of engineering ability. Engineers must have the ability to judge complete plants from the standpoint of... plant location and layout, structural materials, heat economy, automatic control, security and prevention of fires and accidents, as well as productivity, economy, stability and flexibility. In the past these kinds of attributes have been judged by the chemical industry.

The project engineering system is a method of constructing such a highly efficient plant within a reasonable budget and within a prescribed time period. In actual practice, a project team under strict scheduling and control is organized to perform the work of each well-planned stage. Since several years ago, most of the large engineering firms have appropriated the Critical Path Method (CPM) and the Program Evaluation and Review Technique (PERT) (1) for their scheduling and control.

The engineer with complete responsibility of the team is called project manager, who organizes chemical, mechanical, electrical, metallurgical, civil and architectural engineers. Under his responsibility to integrate knowledge of such varied engineering, the project engineering system can provide an effective solution by taking quick and systematic actions in the performance of both design and construction work.

The following presentation will give more precise outline of typical work steps which are served by the engineering firms.

Process Engineering

Process engineering deals with the preparation of an economical basic design when a pilot plant is scaled up for commercial operation, or when a commercial plant is designed based on given conditions. Today, as the scale of modern plants has become larger and highly technical, the performance of process engineering work requires a library of well-organized data, many actual experiences and a more complex organization.

Plant Engineering

In plant engineering, the most efficient materials and equipment are selected from the various alternatives specified by the process engineering. Decisions are also made on the structure and shape of the equipment.

Detailed Engineering

Process engineering and plant engineering are followed by detailed engineering work where thorough knowledge on mechanism, strength, fabrication and construction of structures, vessels, furnaces, piping and utilities, is most essential in performing such work based upon standard specifications.

Procurement

All materials and equipment are purchased from various suppliers. The project teams are directly concerned with the schedule control, cost control and quality control for the successful accomplishment of the projects.

Field Construction

It is possible to construct high quality plants by using the project engineering system to prepare a well balanced design and perform the planned construction work by integrated knowledge of the various engineering fields. Especially in construction work, various jobs are performed at the same time, making it a necessity to obtain the services of an engineering firm that is capable of performing the overall planning and arrangement by controlling the schedule and operation under one single responsibility.

For this thesis, one such engineering firm was selected, to examine its policies for engineering management and to add a new dimension to the management function. Since analysis and experimentation of such firm's operation would be highly complex, a mathematical model to simulate dynamic business activities was built on the basis of the author's past experiences in the chosen Japanese engineering firm.

The primary objective of this study is to aid in developing the needed understanding of the real world system dynamics, and secondly it will provide an opportunity to improve systems behavior under alternate management policies.

The general method of approach selected for this study, due to the magnitude and complexity of the system, is digital computer simulation. The only assumption required is that it is possible to construct a quantitative model of the system which is structurally realistic and which displays dynamic characteristics similar to those of the real system.

Although the model is a simplified picture of reality, it can be quite valuable to gain insights into the dynamic interactions between the firm's management policies which control engineering know-how levels and the work load for engineers, and the number of orders which is influenced by the world situation and the competitiveness of the firm.

CHAPTER II

LITERATURE SURVEY

The literature describing particular applications for management of engineering organizations is now quite extensive and includes such fields as various types of engineering, business administration, and economics. Although the literature on the particular applications has been successful in imparting general knowledge about management of engineering organizations such as network-based management (1), it has not provided the kind of information which is necessary if a top manager wants to know how to proceed in planning its system operations which differ from the special cases cited in the literature. In particular, there exists little literature which relates to design and installation of new management information systems on the basis of the system dynamics of an engineering organization.

Today, however, management of an engineering organization faces a bewildering complexity of change and innovation. Since such an engineering organization not only exists as a corporation but also permeates most companies activity, Karger and Murdick (9) have summarized the responsibility pertinent to management of engineering organization as follows:

1. Ensuring that the corporation will operate in areas of rapidly advancing technology
2. Assuring maximum uses of the company's resources
3. Exploiting fully available as well as potential markets
4. Providing diversification of the company's products
5. Ensuring an increasing profit potential.

To fulfill these prime responsibilities, Karger and Murdick state an engineering organization must recognize:

a. Problems of determining the product such as design problems, manufacturing problems, marketing and product-planning problems, known or anticipated customer wants, long-range business plans, industry trends, technical advances, and competitors' activities.
b. Opportunities now resulting or expected to result from the availability of new knowledge from basic research, new materials, new processes, and advances in the industry which will permit developing and demonstrating the technical feasibility of new and improved products.

In those situations which can be specifically detailed but the overall behavior cannot be described with precision, simulation (13) is an important tool not only for various engineering work but also for management of an engineering organization. One possible simulation technique is the computer simulation of mathematical models. Thus, it is possible to discover with precision the total behavior of many variables interacting in a complex manner.

In order to classify those simulation models, a number of different taxonomic systems have been suggested. For example, Naylor, Balintfy, Burdick, and Chu (13) have classified simulation models as deterministic, stochastic, static and dynamic. Among them a dynamic model is adopted for this study due to gain insight into a complex environment such as an engineering organization. One of the well known theories dealt with dynamic models is Industrial Dynamics (6).

Industrial Dynamics

Industrial Dynamics has been created by the Industrial Dynamics Research Group under the leadership of Forrester (7) at Massachusetts Institute of Technology in 1957. He states Industrial Dynamics in his book as follows:

> Industrial Dynamics is the study of the information-feedback characteristics of industrial activity to show how organizational structure, amplification (in policies), and time delays (in decisions and actions) interact to influence the success of the enterprise. It treats the interactions between the flows of information, money, orders, materials, personnel, and capital equipment in a company, an industry, or a national economy.

In accordance with the philosophy and methodology of Industrial Dynamics, a dynamic simulation model for this study has been developed and analyzed.

CHAPTER III

A DYNAMIC MODEL

An industrial dynamics model of an engineering firm has been developed on the basis of the following background.

The larger operating companies in the process industries, which are described in Chapter I,will ordinarily explore any new process under consideration both technically and economically. However, when an operating company decides to build a complete plant or a single process unit, the engineering firm specializing in such work is usually retained. Numerous variations are possible in the division of work between the operating company (customer) and the engineering firm. The dynamic system structure shown in Figure 1 can be applied to the investigation of managerial policies of such an engineering firm.

Suppose that a customer has decided to construct a plant after economic studies and research on the basis of the world situation. The customer sends out inquiries to several engineering firms which are capable of constructing the plant. Each firm estimates the necessary effort to acquire the order and assigns its engineers to the job. These engineers prepare an estimate for the cost of engineering and construction of the proposed plant. The estimate is presented to the customer in bound form, and negotiation between the customer and each of the firms is performed.

Assuming that the contract is awarded to the firm, the firm then immediately starts estimating the necessary effort to carry out the contract and organizes a project team by acquiring the necessary staff. The project team renders services in accordance with the guarantees from plant consultation to designing, procurement of materials and equipment, construction and test operation. During the project accomplishment, the project progress is periodically evaluated and the firm adjusts the necessary effort. After completion of the project, the plant is turned over to the customer. The performance of the project team strongly influences coming orders.

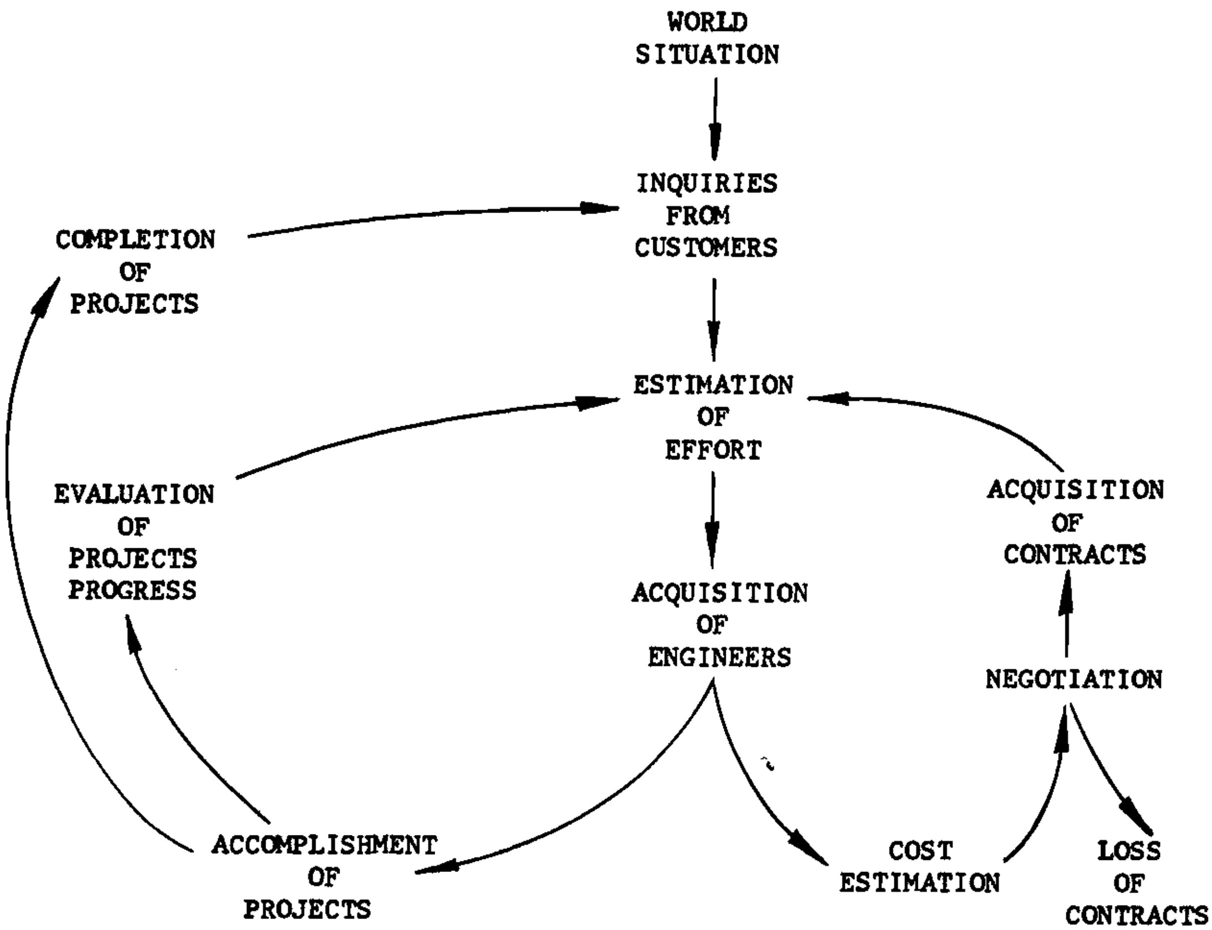


Figure 1. Dynamic System Underlying Project Life Cycle

Problem

The engineering firm depends heavily on human resources more than manufacturing firms. The ability of an individual engineer is closely linked to the overall business performance of the firm. Consequently, management in the firm desires to keep the level of engineering know-how stable while maintaining a stable work load for engineers. However, the firm has had difficulty in attaining stability. When the engineers' work load was heavier due to an increasing incoming contract rate, effort directed to the feedback of know-how became weaker and the know-how level was reduced. On the other hand, when the contract rate decreased, the firm's management put forth a lot of management effort to increase the know-how level. Even though the firm had acquired the latest know-how through the various projects progress, it was difficult to feedback know-how whenever the engineers' work load was heavy. Therefore, the basic problem in determining the firm's policy for feedback of know-how is the double-edged sword nature of the situation. On the one hand, if the firm does not provide adequate engineers to keep the up-to-date know-how level, the long-run ability will be decreased. On the other hand, a very thorough feedback of know-how necessarily removes the most effective engineers from project-oriented works. Different firms try to solve this enigma in different ways, and some simply ignore the existence of the problem. Whatever policy is finally adopted by the firm determines both the future productivity of the firm's engineers, and the current availability of the experienced engineers for project progress.

It is hypothesized that the fluctuation behavior of the know-how level and the work load as shown in Figure 2 is caused by dynamic interaction between the firm's management policies controlling the know-how level and the contract rate which is influenced by the world situation and the competitiveness of the firm.

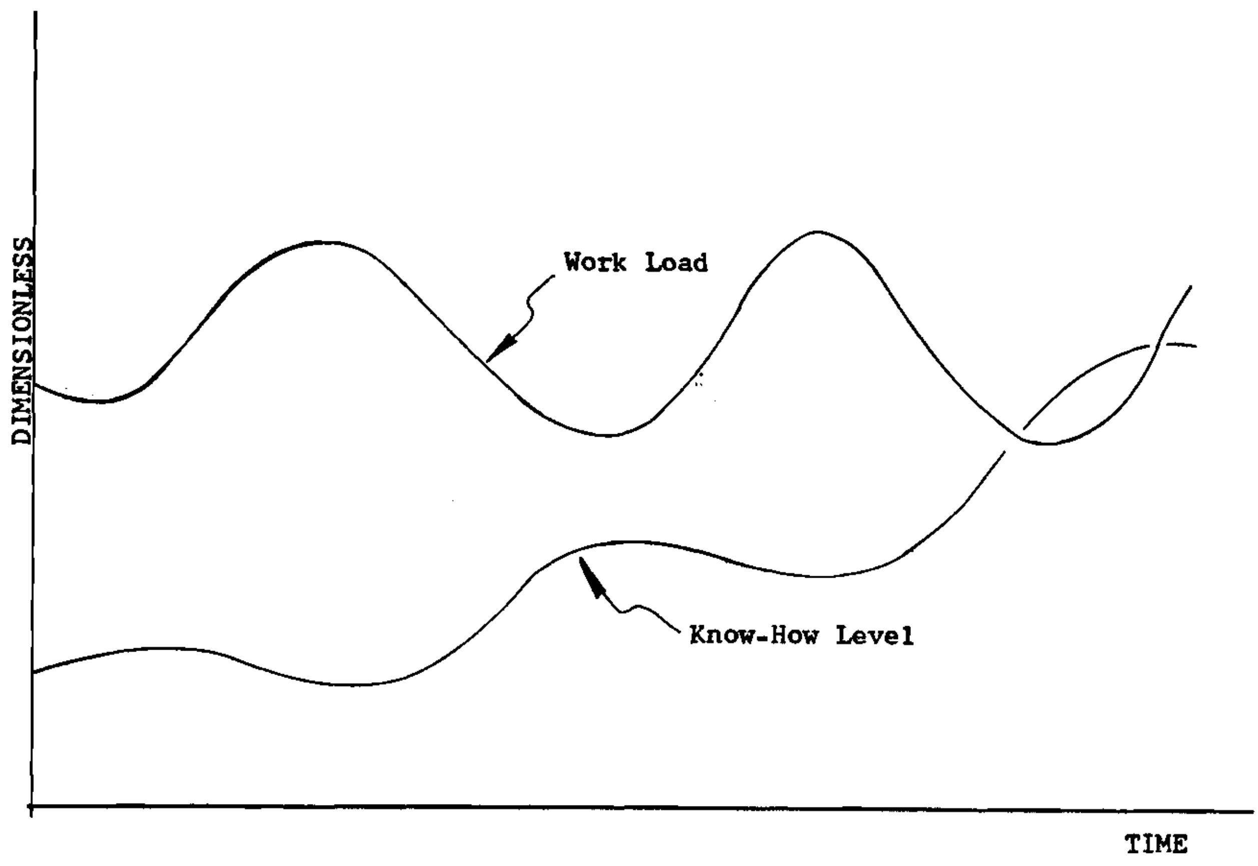


Figure 2. Know-How Level and Work Load Fluctuation

System Structure

Figure 3 illustrates the basic structure which creates the work load fluctuations. The system of interactions contains three basic feedback loops of which two are negative loops and one is a positive loop.

Negative feedback loops have a goal oriented behavior and any deviation from the desired condition is counteracted so that the desired condition is approached. Loops A and C are negative. Loop A dominates long range cyclic behavior and describes the firm's competitiveness to increase or decrease the contract rate. Loop C is a short range loop and describes the situation of an available number of engineers for the project progress. The positive feedback loop has a steady increase or decrease in the same direction. Loop B is positive and dominates short term cyclic behavior.

Loop A involves the interactions between contract rate, projects in progress, work load for engineers, management effort toward feedback of know-how, know-how level, competitiveness, and prospective bids. If the contract rate increases, projects in progress and the work load in turn increase, creating less management effort toward feedback of know-how. When the know-how level decays, causing a drop of competitiveness, prospective bids decrease and later the contract rate falls.

Loop B includes the direct influence of the know-how level on the work load. A lower know-how level increases the quoted work load. The increased work load makes management effort toward feedback reduce, causing a decay of the know-how level. A decrease in the know-how level increases the work load.

Loop C interrelates the work load, management effort toward feedback, and engineers for project teams. If management effort toward feedback increases, engineers are assigned to feedback of know-how. It decreases the available number of engineers for project teams and the work load in turn increases, creating less management effort toward feedback.

It might be expected that the system shown in Figure 3 could create the work load and know-how level fluctuations experienced by the firm.

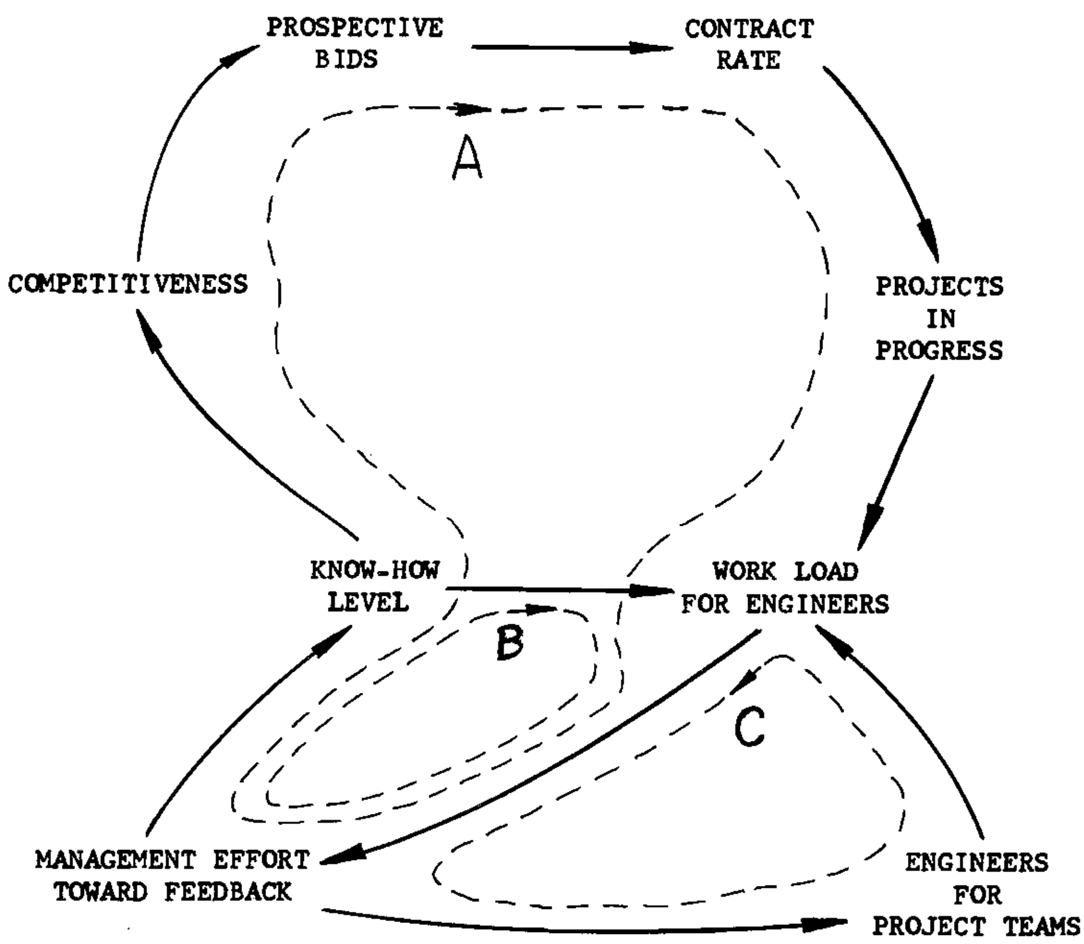


Figure 3. A Basic Structure

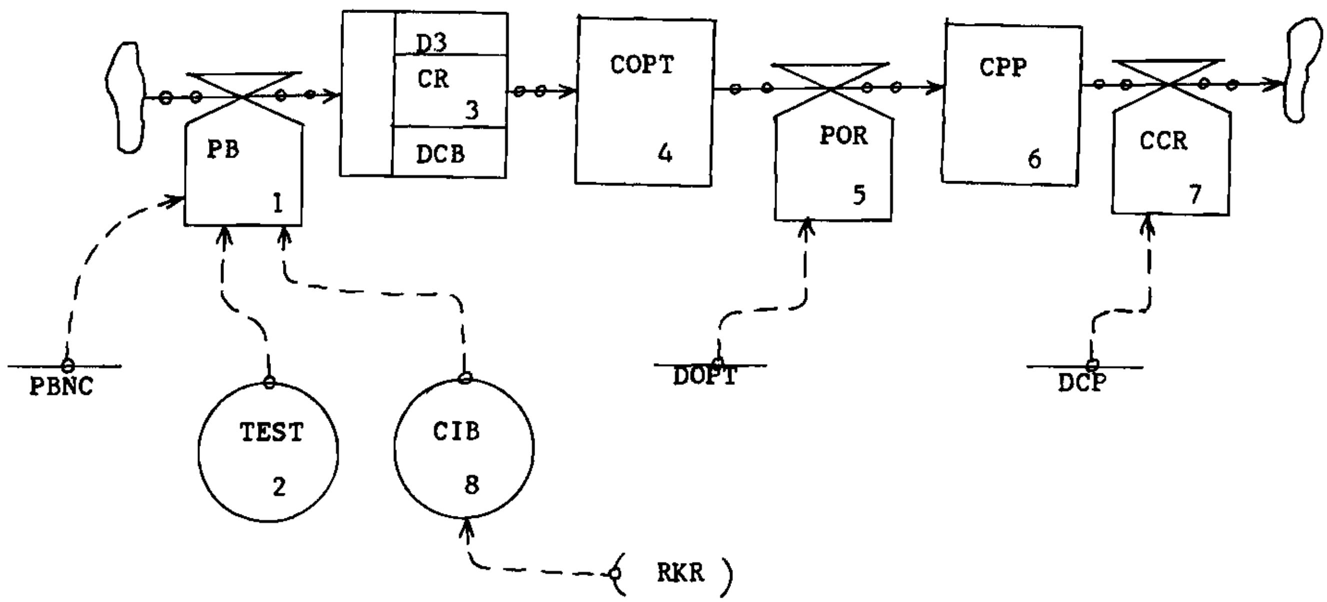
CHAPTER IV

MODEL FORMULATION

This chapter presents in detail the equations which describe the system of interrelationships underlying the engineering firm's fluctuating work load and know-how level. This system is divided into five sectors in which a qualitative description of considerations will be discussed. In addition, a related flow diagram to each sector is illustrated to help understanding of each sector's structure. In order to get a better perspective of these sectional diagrams, an entire flow diagram is shown in Appendix B.

Contract Processing Sector

The engineering firm has operated under the strong influence of the world situation. For instance, a national monetary situation directly influences the customers' investment. In other words, when the government decides to reduce a growth rate of chemical industry, an official interest rate for funds is raised, causing an increase of financial difficulties in the chemical industry. Naturally, the firm cannot improve this situation on its own. On the other hand, although the world situation increases the customers' investment, there is no promise for the firm that its contract rate increases. Consequently, the firm should improve its system to be able to acquire the contracts. The world situation is assumed a constant which was represented by a test input. The model was mainly examined to improve the firm's control system; that is to increase



PBNC .... Prospective Bids Normal Constant (orders/week)
TEST .... Test Input (orders/week)
CIB .... Competitiveness Influence on Bids (dimensionless)
PB .... Prospective Bids (orders/week)
CR .... Contract Rate (orders/week)
DCB .... Delay in Completing a Bid (weeks)
COPT .... Contracts in Organizing Project Teams (orders)
POR .... Project Organizing Rate (orders/week)
DOPT .... Delay in Organizing a Project Team (weeks)
CPP .... Contracts in Project Progress (orders)
CCR .... Contract Completing Rate (orders/week)
DCP .... Delay in Completing a Project (weeks)
RKR .... Relative Know-How Ratio between the Firm and the Customers (dimensionless)

Figure 4. A Flow Diagram of Contract Processing Sector

the contract rate while maintaining a stable work load and level of know-how.

A flow diagram of the contract processing sector is shown in Figure 4.

The number of prospective bids for the firm was generated as a starting point for analysis of the control system. The prospective bids can be considered as the sum of a normal number of bids and a test function. This sum is modified by the influence of the firm's competitiveness.

PB.KL = (CIB.K)(PBNC + TEST.K) 1,R

PBNC = 4

PB .... Prospective Bids (orders/week)
CIB .... Competitiveness Influence on Bids (dimensionless)
PBNC .... Prospective Bids Norman Constant (orders/week)
TEST .... Test Input (orders/week)

The test function is to test the model's sensitivity to external disturbances. A step increase in prospective bids has been selected as the test input to the model. At a time period, say 26 weeks later, a sudden 25 per cent step increase in prospective bids is provided.

TEST.K = STEP (1, 26) 2,A

TEST .... Test Input (orders/week)
STEP .... Functional Notation for Step Function

The prospective bids result in a contract rate with a certain delay. It is assumed there is a two- to four-month delay in an arriving inquiry to the firm. After the firm receives the inquiry from a customer, it takes an additional two to four months to complete the bid. This involves a cost estimation and negotiation time. This can be written as a third-order delay (6).

CR.KL = DELAY 3(PB.JK, DCB) 3,R

DCB = 26

CR .... Contract Rate (orders/week)
PB .... Prospective Bids (orders/week)
DCB .... Delay in Completing a Bid (weeks)
DELAY3 .... Dynamo Notation for a Third-Order Exponential Delay

When the order is acquired, a project team is organized in the firm. Actually each order has different aspects such as individual conditions of a location site, engineering difficulties, a construction period, a budget, and so forth. In this model, however, all orders are assumed to be of the same kind in order to study the control system problems more precisely.

An order from the customer stays in the waiting line until a project team is organized and the necessary engineers are assigned. Thus, the number of contracts in waiting is described as follows:

COPT.K = COPT.J + (DT)(CR.JK - POR.JK) 4,L

COPT = 5 4,N

COPT .... Contracts in Organizing Project Teams (orders)
CR .... Contract Rate (orders/week)
POR .... Project Organizing Rate (orders/week)

In general, each project team is organized for a cost estimation and negotiation after the firm receives an inquiry. But the team is rather small at this stage. After the contract is established, a formal project team is organized. There exists about two weeks delay in order to acquire the necessary staff for a project team.

POR.KL = COPT.K/DOPT 5,R

DOPT = 2

POR .... Project Organizing Rate (orders/week)
COPT .... Contracts in Organizing Project Teams (orders)
DOPT .... Delay in Organizing a Project Team (orders)

The number of contracts in project progress increases by the project organizing rate and decreases by the contract completing rate.

$$CPP.K = CPP.J + (DT)(POR.JK - CCR.JK) \qquad 6,L$$

$$CPP = 90 \qquad 6,N$$

CPP ....Contracts in Project Progress (orders)
POR .... Project Organizing Rate (orders/week)
CCR .... Contract Completing Rate (orders/week)

During the project progress, the following works which are described in detail in Chapter I are usually carried out.

* Completion of the contract documents
* Process Engineering
* Plant Engineering
* Detailed Engineering and Drafting
* Procurement and Inspection
* Field Construction and Inspection
* Test Operation

There are a lot of variations of the contract period depending on the customer. The period is determined mostly by the customer's will before the contract is set up. The average delay in completing a project is assumed to be six months which actually varies from three months to two years.

$$CCR.KL = CPP.K/DCP \qquad 7,R$$

$$DCP = 26$$

CCR .... Contract Completing Rate (orders/week)
CPP .... Contracts in Project Progress (orders)
DCP .... Delay in Completing a Project (weeks)

It is assumed that the relative know-how ratio between the firm and the customers directly influences the firm's competitiveness. If the firm's know-how level is above the customer's expectation to the engineering firms, the firm's competitiveness would go up.

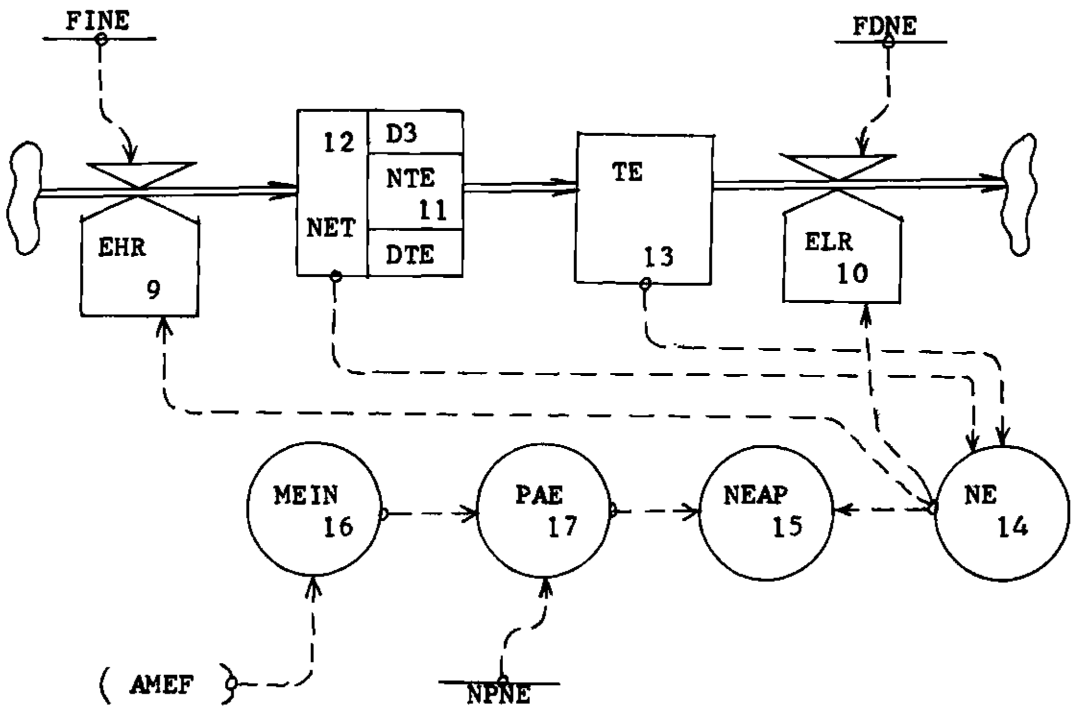
$$CIB.K = 1/RKR.K \qquad 8,A$$

CIB .... Competitiveness Influence on Bids (dimensionless)
RKR .... Relative Know-How Ratio between the Firm and the Customers (dimensionless)

Engineers Acquisition Sector

The most critical productive project resource is engineering manpower. In the past the firm had increased rather rapidly the number of engineers in accordance with the increased orders. Since several years ago the firm's management has been performing its effort toward training and utilizing the engineers recruited in lieu of hiring many engineers because the firm's management recognized that the number of engineers had reached the desired level. As high knowledge is necessary when dealing with overall planning and designing of complete process plants, a long training period is required of engineers before they are utilized. Therefore, the firm's hiring and firing of engineers is rather stable regardless of the number of orders. To the firm, the stability of the engineering group over a long period is a more important influence on its hiring policies than is the fluctuation of the number of orders. A flow diagram of the engineers acquisition sector is illustrated in Figure 5.

The annual hiring rate of new engineers is actually equal to about five per cent of the number of engineers which are already employed. On the other hand, about three per cent of employed engineers leave the firm during the year. It is assumed that engineers are equally hired or fired throughout the year.



EHR .... Engineers Hiring Rate (men/week)
FINE .... Fractional Increase in Number of Engineers (1/week)
NET .... Number of Engineers in Training (men)
NTE .... Newly Trained Engineers (men/week)
DTE .... Delay in Training Engineers (weeks)
TE .... Trained Engineers (men)
ELR .... Engineers Leaving Rate (men/week)
FDNE .... Fractional Decrease in Number of Engineers (1/week)
NE .... Number of Engineers (men)
NEAP .... Number of Engineers for Assigning to Project Teams (men)
PAE .... Percentage of Assigning Engineers for Projects Progress (per cent)
NPNE .... Normal Percentage of Number of Engineers for Projects Progress (dimensionless)
MEIN .... Management Effort Influence on Number of Engineers for Projects Progress (dimensionless)
AMEF .... Average Management Effort toward Feedback (managerial time/week)

Figure 5. A Flow Diagram of Engineers Acquisition

$$EHR.KL = (FINE)(NE.K) \qquad 9,R$$

$$FINE = .0010$$

$$ELR.KL = (FDNE)(NE.K) \qquad 10,R$$

$$FDNE = .0006$$

EHR .... Engineers Hiring Rate (men/week)
FINE .... Fractional Increase in Number of Engineers (1/week)
NE .... Number of Engineers (men)
ELR .... Engineers Leaving Rate (men/week)
FDNE .... Fractional Decrease in Number of Engineers (1/week)

Most new engineers are recruited directly from college. Even though some of the new engineers had experience from other companies, the firm recognizes a need for orienting and training them. Consequently, the new engineers do not become productive at once. After the short-term training programs, the firm allocates the new personnel to work with the experienced engineers available. It is assumed that there is a constant average training delay which is approximately three years. For simplicity it is also assumed that no engineers leave the firm during the training period.

$$NTE.KL = DELAY3\ (EHR.JK,\ DTE) \qquad 11,R$$

$$NET.K = NET.J + (DT)(EHR.JK - NTE.JK) \qquad 12,L$$

$$NET = (EHR)(DTE) \qquad 12,N$$

$$DTE = 156$$

EHR .... Engineers Hiring Rate (men/week)
NTE .... Newly Trained Engineers (men/week)
DTE .... Delay in Training Engineers (weeks)
NET .... Number of Engineers in Training (men)
DELAY3 .... Functional Notation

The number of trained engineers is described by a level equation with an inflow of newly trained engineers and an outflow of engineers leaving the firm.

$$TE.K = TE.J + (DT)(NTE.JK - ELR.JK) \qquad 13,L$$

$$TE = 950$$

TE .... Trained Engineers (men)
NTE .... Newly Trained Engineers (men/week)
ELR .... Engineers Leaving Rate (men/week)

The total number of engineers equals the sum of the engineers in training and the trained engineers.

$$NE.K = NET.K + TE.K \qquad 14,A$$

NE .... Number of Engineers (men)
NET .... Number of Engineers in Training (men)
TE .... Trained Engineers (men)

The number of engineers available for assignment to the project teams varies by the firm's management policies. The number of engineers is therefore equal to the total number of engineers multiplied by the percentage of the number of engineers for projects progress.

$$NEAP.K = (PAE.K)(NE.K) \qquad 15,A$$

NEAP .... Number of Engineers for Assigning to Project Teams (men)
PAE .... Percentage of Assigning Engineers for Projects Progress (per cent)
NE .... Number of Engineers (men)

It is assumed that seventy per cent of engineers are kept in the engineers' pool for projects progress, twenty-five per cent of engineers are assigned for the firm's research and development projects, and five per cent of engineers are needed for other works which are mainly top management and indirect or staff working. It is presumed that engineers of the research and development groups are not transferred to the project teams. However, the firm's management often changes those percentages in response to the work load. When management effort toward feedback of know-how increases, the number of engineers for projects progress decreases and management assigns more engineers for implementing feedback of know-how.

On the other hand, if management effort toward feedback decreases, more engineers are assigned for projects progress. Figure 6 shows the relationships between the number of engineers for projects progress and average management effort toward feedback of know-how.

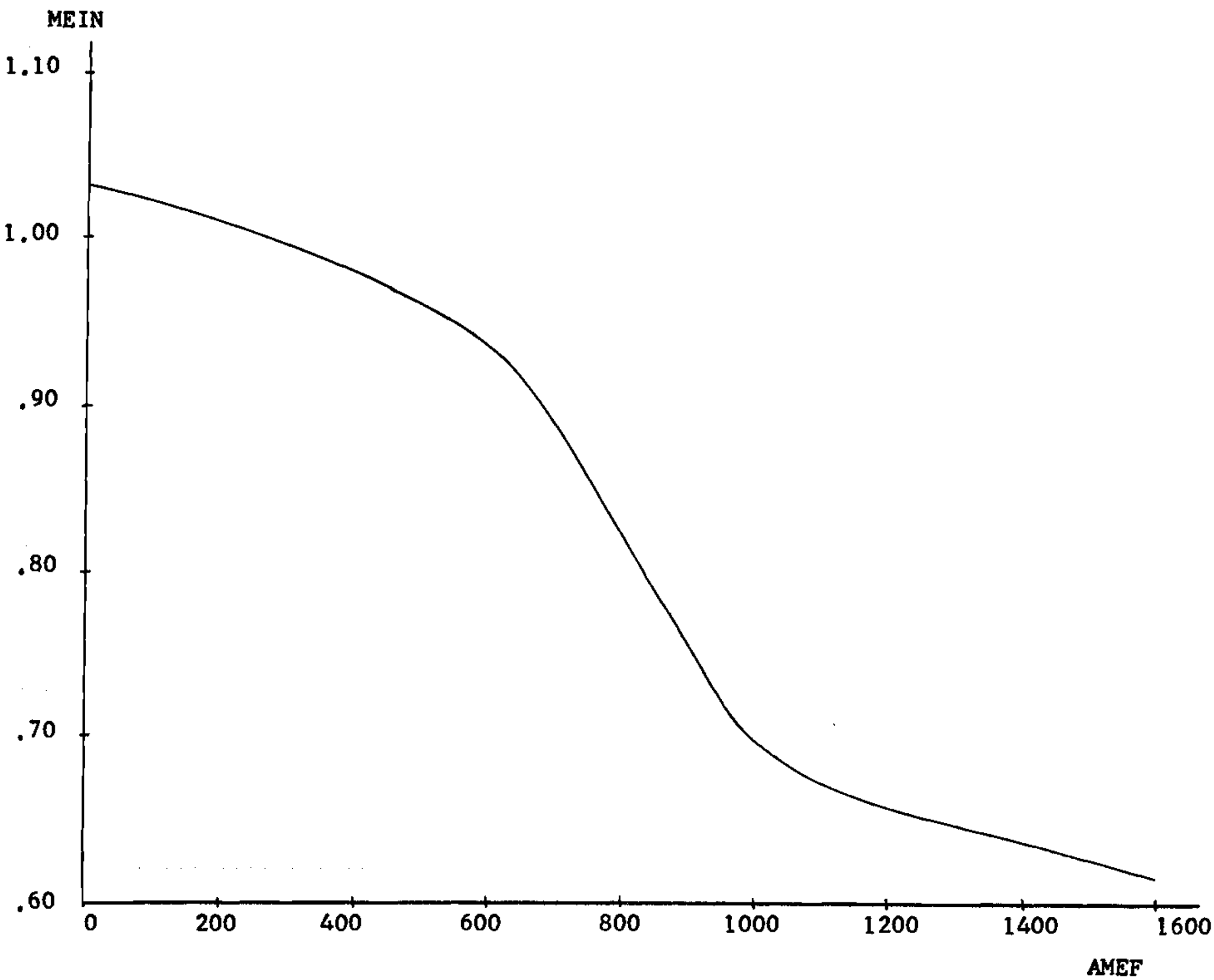


Figure 6. Fraction of Engineers vs. Average Management Effort

MEIN.K = TABHL (TBMEN, AMEF.K,0, 1600, 200) 16,A

TBMEN * = 1.03/1.01/.98/.94/.82/.70/.66/.64/.62

MEIN .... Management Effort Influence on Number of Engineers for Projects Progress (dimensionless)
AMEF .... Average Management Effort toward Feedback (managerial time/week)
TBMEN .... Table for MEIN (see Figure 6)
TABHL .... Functional Notation

The percentage of the number of engineers for projects progress is therefore equal to the normal percentage multiplied by management effort influence on the number of engineers for projects progress.

PAE.K = (NPNE)(MEIN.K) 17,A

NPNE = .70

PAE .... Percentage of Assigning Engineers for Projects Progress (per cent)
NPNE .... Normal Percentage of Number of Engineers for Projects Progress (dimensionless)
MEIN .... Management Effort Influence on Number of Engineers for Projects Progress (dimensionless)

Work Load Determination Sector

Figure 7 depicts the work load determination sector. The work load is determined by the number of engineers available, the number of project teams in progress and the engineering know-how level. It is assumed that six engineers including engineers in training are needed for a project team during project progress because the firm always acquires just one kind of contract as mentioned previously. Therefore, the engineers assigning rate is formulated as the multiplication of six engineers by the project organizing rate.

EAR.KL = (NENC)(POR.JK) 18,R

NENC = 6

EAR .... Engineers Assigning Rate (men/week)
NENC .... Number of Engineers Needed per Contract (men/order)
POR .... Project Organizing Rate (orders/week)

The engineers releasing rate is also obtained by the multiplication of six engineers by the project completing rate.

ERR.KL = (NENC)(CCR.JK) 19,R

ERR .... Engineers Releasing Rate (men/week)
NENC .... Number of Engineers Needed per Contract (men/order)
CCR .... Contract Completing Rate (orders/week)

The firm has been experiencing overtime over a long period. The number of engineers occupied for project teams is an artificial number to demonstrate the firm's overtime situation. In other words, this number can be more than the actual number of engineers.

NEOP.K = NEOP.J + (DT)(EAR.JK - ERR.JK) 20,L

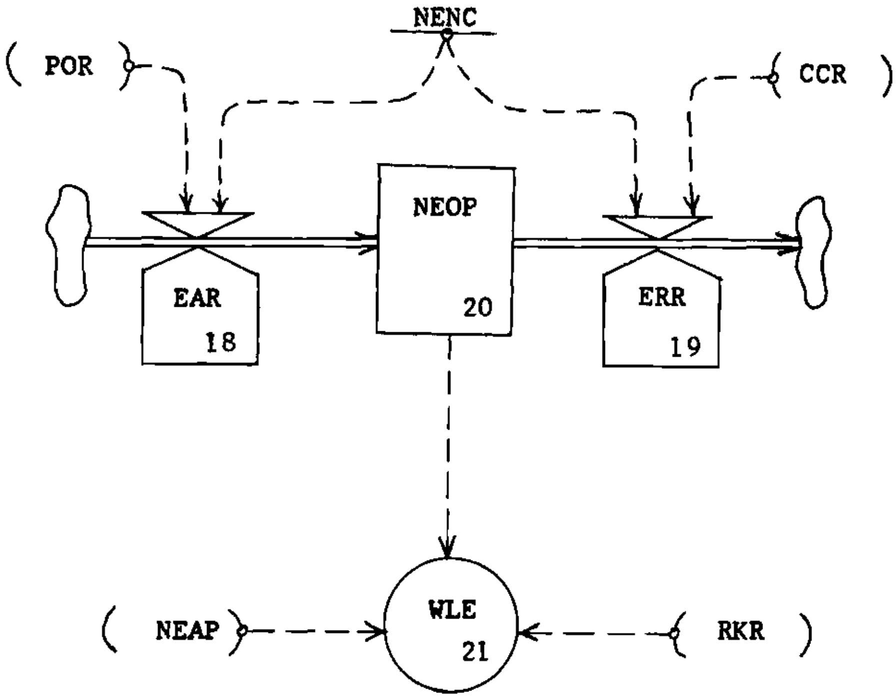
NEOP = 540 20,N

NEOP .... Number of Engineers Occupied for Project Teams (men)
EAR .... Engineers Assigning Rate (men/week)
ERR .... Engineers Releasing Rate (men/week)

Having project experience and up-to-date written forms of know-how, the firm's engineers improve their skill to carry out the contracts. It provides for more effective and rapid accomplishment of the contracts. On the other hand, the customers' expectation of the know-how level of the firm is also increasing. Consequently, the relative know-how ratio between the customers and the firm influences the work load.

WLE.K = (RKR.K)(NEOP.K)/NEAP.K 21,A

WLE .... Work Load for Engineers (dimensionless)
RKR .... Relative Know-How Ratio between the customers and the firm (dimensionless)
NEOP .... Number of Engineers Occupied for Project Teams (men)
NEAP .... Number of Engineers for Assigning to Project Teams (men)



EAR .... Engineers Assigning Rate (men/week)
POR .... Project Organizing Rate (orders/week)
NENC .... Number of Engineers Needed per Contract (men/order)
NEOP .... Number of Engineers Occupied for Project Teams (men)
ERR .... Engineers Releasing Rate (men/week)
CCR .... Contract Completing Rate (orders/week)
WLE .... Work Load for Engineers (dimensionless)
NEAP .... Number of Engineers for Assigning to Project Teams (men)
RKR .... Relative Know-How Ratio between the customers and the firm (dimensionless)

Figure 7. A Flow Diagram of Work Load Determination

Management Effort Sector

The firm's engineers, who are assigned to project teams, are improving their know-how level through project experience. The know-how level as a total system, however, cannot be effectively improved unless the firm's management efforts are executed to carrying out systematic feedback of know-how. It is assumed that such management effort is dependent on the average work load. If the average work load increases, management is required to spend most of its time carrying out the orders, and little effort is available for implementing feedback of know-how. Some feedback is still carried out, because a few engineers are particularly assigned to this function. Nevertheless, if the average work load becomes extremely heavy, those engineers are also transferred to project teams, causing no effort toward feedback.

Figure 8 shows a flow diagram of the management effort sector. The average work load is a short-term average of the work load. It can be written as a first-order exponential smoothing equation.

AWLE.K = AWLE.J + (DT)(1/DAWLE)(WLE.J - AWLE.J)   22,L

AWLE = 0.89

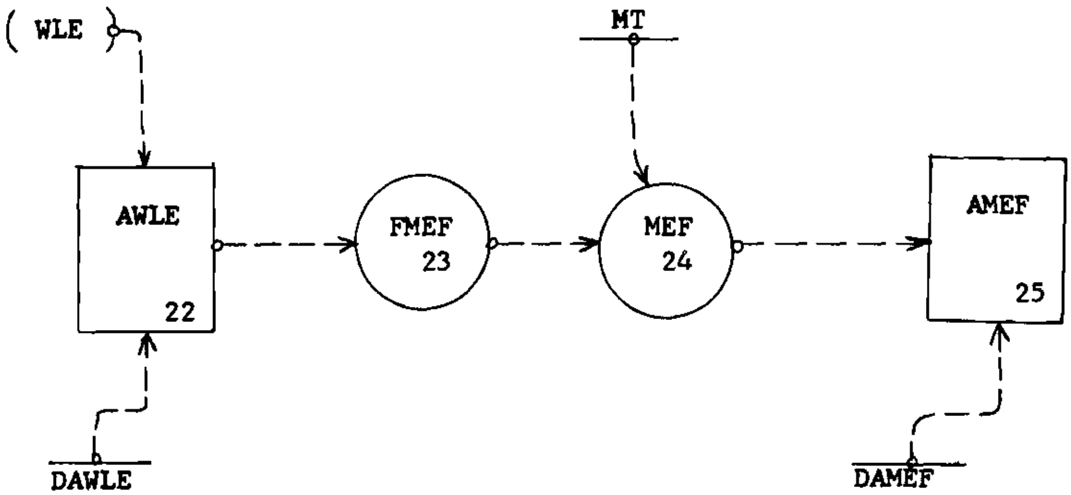
DAWLE = 4

AWLE .... Average Work Load for Engineers (dimensionless)
WLE .... Work Load for Engineers (dimensionless)
DAWLE .... Delay in Averaging Work Load for Engineers (weeks)

Figure 9 shows the relationship between fraction of management effort toward feedback and the average work load.

FMEF.K = TABHL (TBFME, AWLE.K, 0, 3, 0.3)   23,A

TBFME* = .35/.34/.315/.26/.06/.02/.008/0/0/0/0



WLE .... Work Load for Engineers (dimensionless)
AWLE .... Average Work Load for Engineers (dimensionless)
DAWLE .... Delay in Averaging Work Load for Engineers (weeks)
FMEF .... Fraction of Management Effort toward Feedback of Know-How (dimensionless)
MEF .... Management Effort toward Feedback of Know-How (managerial time/week)
AMEF .... Average Management Effort toward Feedback (managerial time/week)
DAMEF .... Delay in Averaging Management Effort toward Feedback (weeks)
MT .... Managerial Time (managerial time/week)

Figure 8. A Flow Diagram of Management Effort

FMEF .... Fraction of Management Effort toward Feedback of Know-How (dimensionless)
AWLE .... Average Work Load for Engineers (dimensionless)
TBFME .... Table for FMEF (see Figure 9)

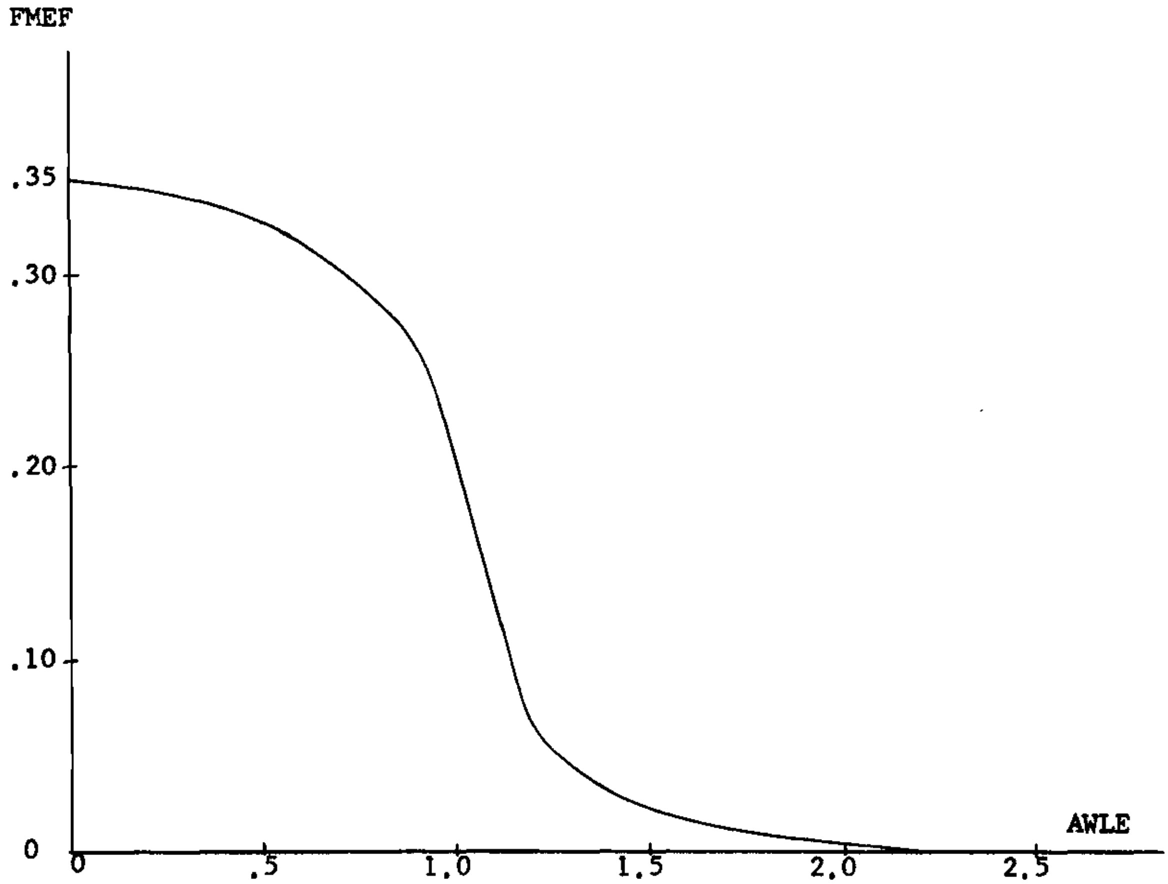


Figure 9. Management Effort vs. Average Work Load

The amount of effort toward feedback is therefore equal to the total amount of managerial time multiplied by the fraction toward feedback.

MEF.K = (FMEF.K)(MT) 24,A

MT = 3800

MEF .... Management Effort toward Feedback of Know-How (managerial time/week)
FMEF .... Fraction of Management Effort toward Feedback of Know-How (dimensionless)
MT .... Managerial Time (managerial time/week)

The level of know-how does not respond immediately to changes in quoted management effort. It is some average value of the quantity that influences the know-how level.

AMEF.K = AMEF.J + (DT)(1/DAMEF)(MEF.J - AMEF.J)   25,L

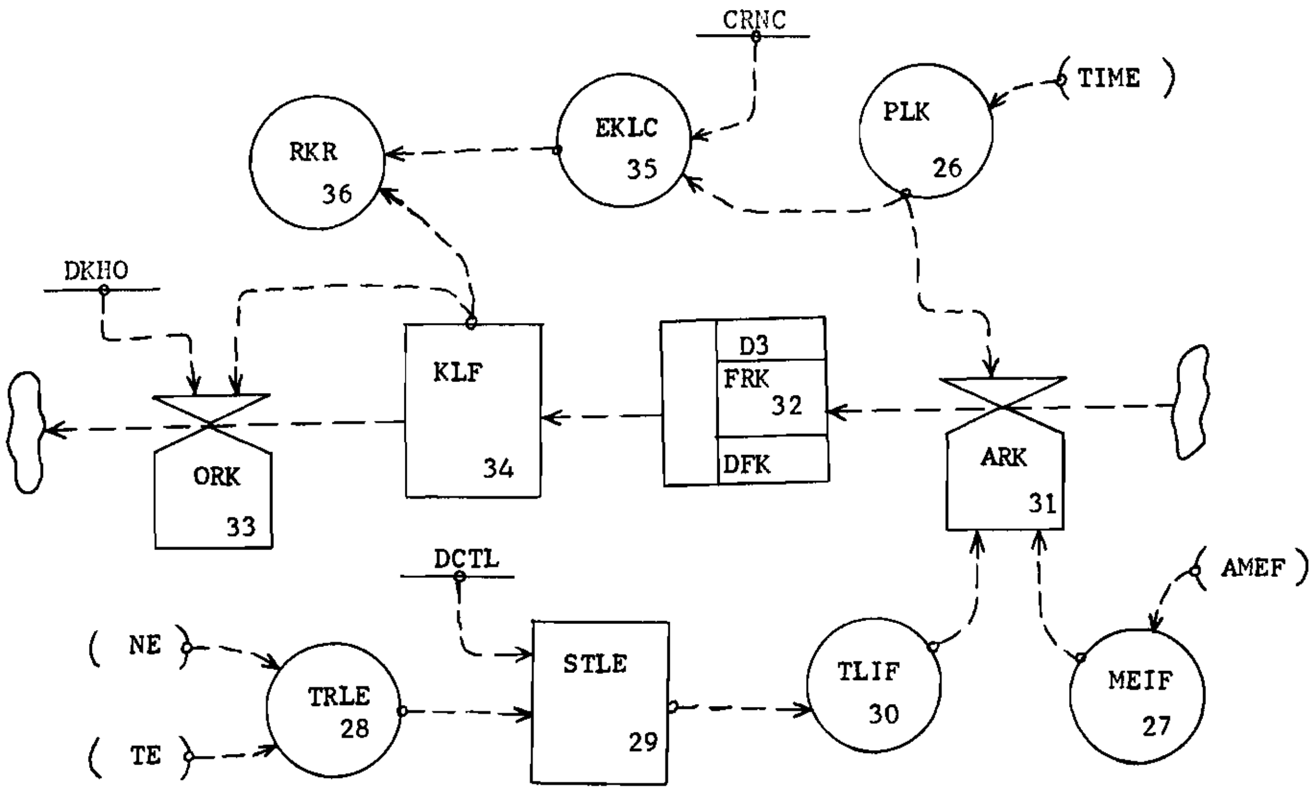
AMEF = MEF   25,N

DAMEF = 4

AMEF .... Average Management Effort toward Feedback (managerial time/week)
MEF .... Management Effort toward Feedback of Know-How (managerial time/week)
DAMEF .... Delay in Averaging Management Effort toward Feedback (weeks)

Engineering Know-How Sector

Any discussion of engineering productivity tends inherently to become highly complex for two reasons. First, there exists little agreement (despite vast research) about the determinants of human productivity. Second, one of the few general agreements is that the influences upon productivity of engineers are both numerous and highly unstructured. Effective engineering productivity is believed to be dependent on the number of engineers, the degree to which engineers possess utilizable skill, and the general level of the potential technological utilization (17). The number of engineers is discussed in the engineers' acquisition sector. As mentioned in the management effort sector, engineers assigned to project teams improve their engineering skill by getting know-how from the customers, the suppliers, engineers in the firm itself, and by the materials published during project accomplishment. The general level of the



ARK .... Acquisition Rate of Know-How (1/week)
MEIF .... Management Effort Influence on Feedback (1/week)
TLIF .... Trained Level Influence on Feedback (dimensionless)
PLK .... Potential Level of Know-How (dimensionless)
TIME .... Dynamo simulation Time Notation (week)
FRK .... Feedback Rate of Know-How (1/week)
DFK .... Delay in Feedback of Know-How (weeks)
KLF .... Know-How Level by Feedback (dimensionless)
ORK .... Obsolescence Rate of Know-How (1/week)
DKHO .... Delay in Know-How Obsolescence (weeks)
EKLC .... Expected Know-How Level by the Customers (dimensionless)
CRNC .... Customers Recognition Normal Constant (dimensionless)
RKR .... Relative Know-How Ratio between the Firm and the Customers (dimensionless)
TRLE .... Trained Level of Engineers (dimensionless)
STLE .... Smoothed Trained Level of Engineers (dimensionless)
NE .... Number of Engineers (men)
TE .... Trained Engineers (men)
DCTL .... Delay in Changing Trained Level (weeks)
AMEF .... Average Management Effort toward Feedback (managerial time/week)

Figure 10. A Flow Diagram of Acquiring Know-How

potential technological utilization is considered in this model as the up-to-date know-how level. A flow diagram of engineering know-how sector is illustrated in Figure 10.

It is assumed that a customer holds a very high know-how level in the petroleum and chemical industry. Figure 11 shows the assumed development of that customer's know-how level.

```
PLK.K = TABHL (TBPLK, TIME.K, 0, 520,40)          26,A

TBPLK* = .38/.40/.43/.46/.49/.52/.56/.60/
         .65/.70/.76/.83/.91/1.00
```

PLK .... Potential Level of Know-How (dimensionless)
TIME .... Dynamo Simulation Time Notation (week)
TBPLK .... Table for PLK (see Figure 11)

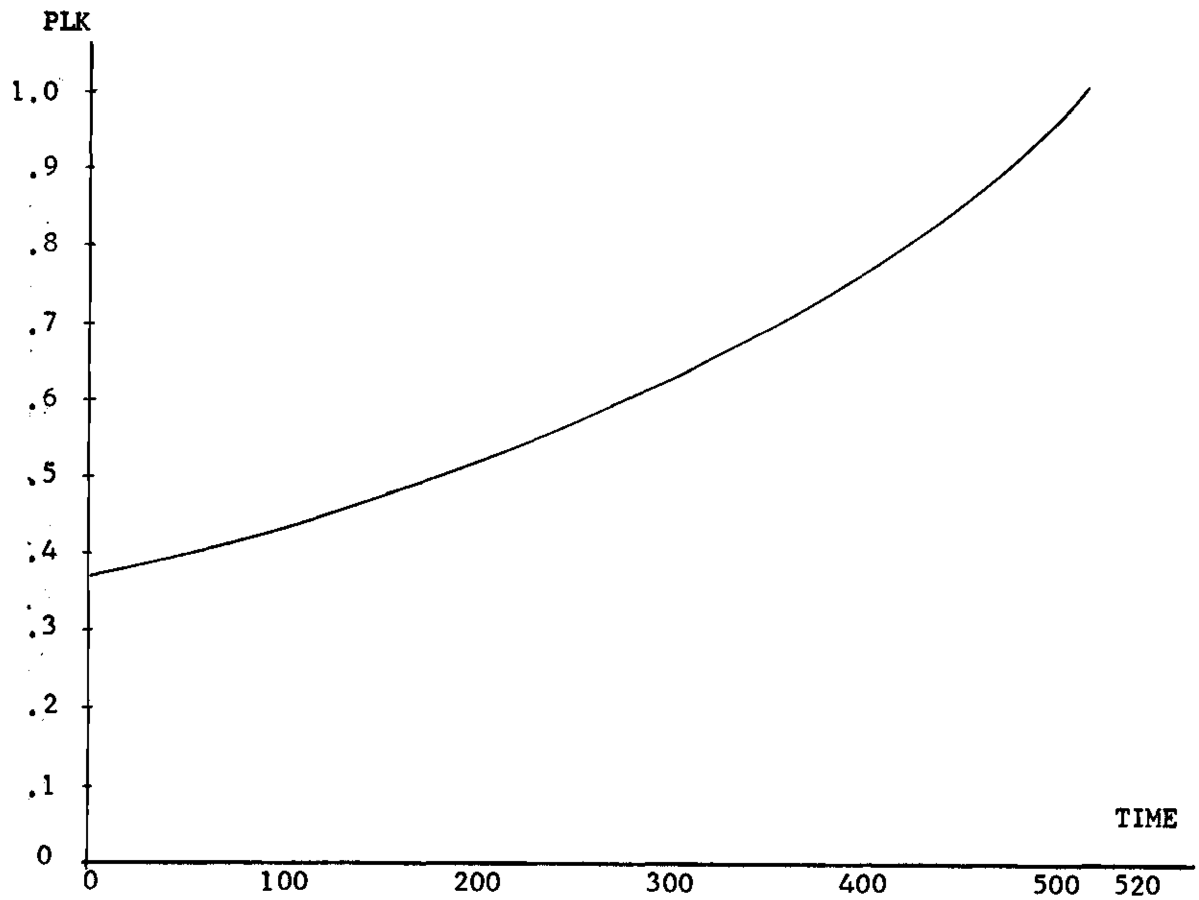


Figure 11. Development of the Potential Know-How Level

Although the firm owns the research and development center, it is limited in its ability to get effective data of the operation and maintenance of various plants. Since these data influence the engineering know-how level, it is assumed that the firm cannot improve it's know-how level more than the potential know-how level during the simulation time. Figure 12 depicts the percentage of the know-how level which the firm can acquire by it's feedback effort. The amount of feedback is directly dependent on average management effort directed toward feedback of know-how.

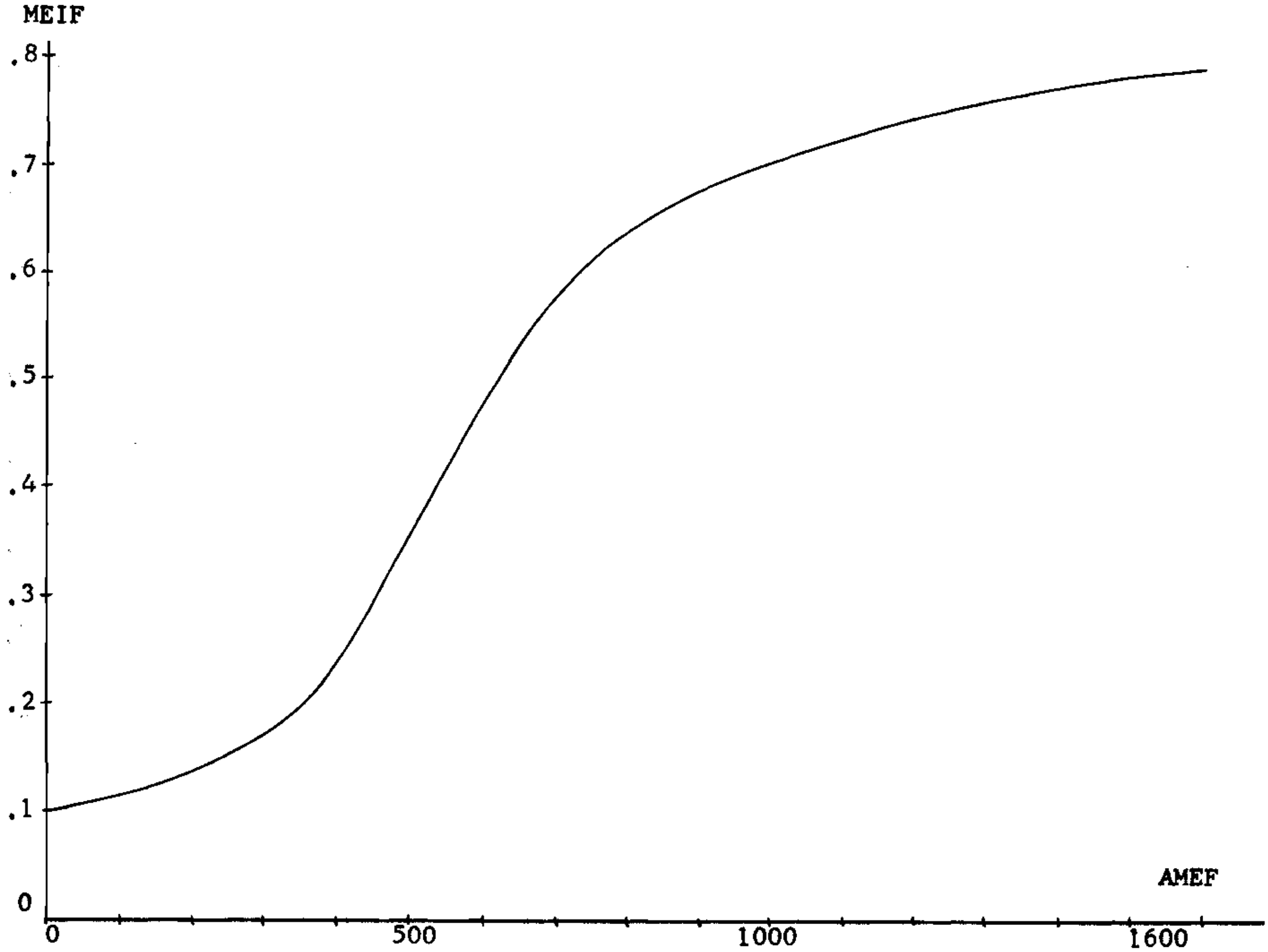


Figure 12. Management Effort Influencing Know-How Level vs. Average Management Effort

MEIF.K = TABHL (TBMEF, AMEF.K, 0, 1600, 200) 27,A

TBMEF* = .10/.14/.24/.48/.64/.70/.74/.76/.78

MEIF .... Management Effort Influence on Feedback (1/week)
AMEF .... Average Management Effort toward Feedback (managerial time/week)

The trained level of engineers also influences feedback. For simplicity it is assumed that the trained level can be written as a ratio between the total number of engineers and the number of trained engineers.

TRLE.K = TE.K/NE.K 28,A

TRLE .... Trained Level of Engineers (dimensionless)
TE .... Trained Engineers (men)
NE .... Number of Engineers (men)

It is some average value of the ratio that influences feedback effort, because some engineers are accustomed to work for feedback but some are not.

STLE.K = STLE.J + (DT)(1/DCTL)(TRLE.J - STLE.J) 29,L

STLE = TRLE 29,N

DCTL = 4

STLE .... Smoothed Trained Level of Engineers (dimensionless)
TRLE .... Trained Level of Engineers (dimensionless)
DCTL .... Delay in Changing Trained Level (weeks)

The fractional influence of the trained level toward feedback is illustrated in Figure 13.

TLIF.K = TABHL (TBTLF, STLE.K, 0, 1.0, .2) 30,A

TBTLF* = .02/.035/.05/.06/.07/.08/.087/
.093/.10/.11/.13

TLIF .... Trained Level Influence on Feedback (dimensionless)
STLE .... Smoothed Trained Level of Engineers (dimensionless)
TBTLF .... Table for TLIF (see Figure 13)

By combining all these influences on feedback ----- the potential level of know-how of PLK, management effort influence on feedback of MEIF,

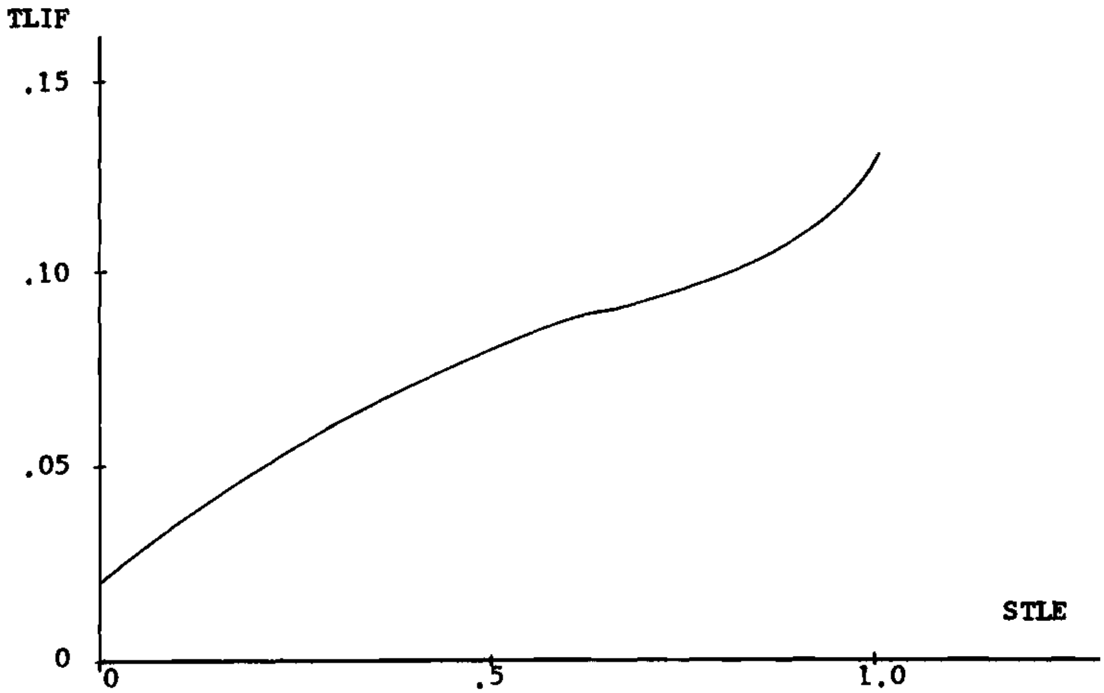


Figure 13. Fractional Influence toward Feedback vs. Smoothed Trained Level

and the trained level influence on feedback of TLIF ----- the equation is written for the acquisition rate of know-how.

ARK.KL = (PLK.K)(MEIF.K)(TLIF.K) 31,R

ARK .... Acquisition Rate of Know-How (1/week)
PLK .... Potential Level of Know-How (dimensionless)
MEIF .... Management Effort Influence on Feedback (1/week)
TLIF .... Trained Level Influence on Feedback (dimensionless)

In all likelihood, a couple of months goes by before the engineers on the projects are able to utilize effectively new or revised know-how on the project problem. A typical method of feedback for know-how is to prepare in written form such as standard specifications, manuals, and the like. Thus, the delay in feedback of know-how also includes the time of writing, discussing, compiling, printing, and distribution. The delay is assumed to be about nine months.

FRK.KL = DELAY 3(ARK.JK, DFK) 32,R

DFK = 39

FRK .... Feedback Rate of Know-How (1/week)
ARK .... Acquisition Rate of Know-How (1/week)
DFK .... Delay in Feedback of Know-How (weeks)
DELAY3 .... Functional Notation

Know-how gained by feedback effort in general becomes obsolete with the passing time, because of the rapid technological development. It is assumed that the average obsolescent time of know-how is a year. It takes thirty-nine weeks, as mentioned above, for the engineers to utilize new or revised know-how after the engineering data or materials are acquired through project accomplishment. DKHO is therefore actually thirteen weeks.

ORK.KL = KLF.K/DKHO 33,R

DKHO = 13

ORK .... Obsolescence Rate of Know-How (1/week)
KLF .... Know-How Level by Feedback (dimensionless)
DKHO .... Delay in Know-How Obsolescence (weeks)

The effective know-how level is formulated as a regular level equation with an inflow of newly gained know-how and an outflow of obsolescent know-how.

KLF.K = KLF.J + (DT)(FRK.JK - ORK.JK) 34,L

KLF = .15

KLF .... Know-How Level by Feedback (dimensionless)
FRK .... Feedback Rate of Know-How (1/week)
ORK .... Obsolescence Rate of Know-How (1/week)

As a matter of fact, there are various customers on different know-how levels. It is therefore assumed that the average expectation of the know-how level of the engineering firms by the general customers is fifty per cent of PLK.

EKLC.K = (CRNC)(PLK.K) 35,A

CRNC = .50

EKLC .... Expected Know-How Level by the Customers (dimensionless)
CRNC .... Customers Recognition Normal Constant (dimensionless)
PLK .... Potential Level of Know-How (dimensionless)

The relative know-how ratio between the customers and the firm is taken to be a function of the know-how level affecting the work load and the firm's competitiveness.

RKR.K = EKLC.K/KLF.K 36,A

RKR .... Relative Know-How Ratio between the Firm and the Customers (dimensionless)
EKLC .... Expected Know-How Level by the Customers (dimensionless)
KLF .... Know-How Level by Feedback (dimensionless)

This completes the equation writing and parameter specification describing the model.

CHAPTER V

ANALYSIS OF THE MODEL

On the basis of the hypothesis pertinent to the system structure for the engineering firm, a model of the interactions has been developed in the previous chapter. This chapter deals with the behavior of the model in order to demonstrate how the interactions between the number of orders and the know-how level produce fluctuations in the work load and management effort toward feedback of know-how.

The first simulation run indicates the behavior of the model in response to a 25 per cent step increase in prospective bids. The second and third runs simulate the behavior of the model with changes in two parameters, which are the delay in feedback of know-how, and the delay in know-how obsolescence.

For the second and third run, it is assumed that the average obsolescence time of know-how is a month and a half longer than the basic model. By changing those parameters, it can be observed how the timing of feedback of know-how affects the firm's performance in terms of the contract rate and the work load for engineers.

The time unit selected for iterative calculation purposes was one week and the simulated time was selected to be 10 years.

Behavioral Analysis for the Step Input (Run 1)

A step increase in prospective bids has been selected as the test input to the model. Figure 14 shows the basic model behavior which was set up exactly as described in the previous chapter. The 25 per cent step input figure was arbitrarily chosen to be the driving function throughout the remainder of the model analysis.

As a general overview, the pattern of the curve representing the work load for engineers should be noted. Within a period (week 5 thru 80) the work load is no more than 1.0, which implies no overtime on an average exists in the firm. This causes a high know-how level and an increase in the contract rate. Although the contract rate rather rapidly increases by the test input introduced at week 26, the contract rate starts to increase in advance at week 15. This is caused by the increasing competitiveness. After the contract rate reaches the first peak which equals 5.8 at week 75, development of the know-how level also reaches a peak and starts to decrease causing an increase in the work load. At week 220 the work load reaches a peak, causing no management effort toward feedback of know-how. That reduces the contract rate to about 0.9 orders per week which indicates a serious situation in the firm. The work load naturally declines to a bottom of 0.43 at week 375. The firm does not fire any engineers during the short-term fluctuation due to its management policy which was mentioned in the engineers acquisition sector of Chapter IV. Thus, its management seeks to utilize the idle engineers. A typical way of utilizing engineers is to carry out feedback of know-how. Management also recognizes that there exists a large gap in the know-how levels of the firm and the customers because of the declining order rate. Thus, from week 260 to week 380 it is observed that management effort toward feedback rather rapidly increases and reaches the second peak at week 380. The know-how level starts to increase by strong effort toward feedback of know-how, causing an increase in the competitiveness and then the contract rate. At week 475 the know-how level and the contract rate reach their second peak, causing an increase in the work load again. It is interesting to note that this is approximately the same work load pattern which has been experienced by the firm.

By referring to Figure 14, a more detailed description of the behavior will be presented. Although overtime on an average does not show up during a period (week 5 thru 80), the work load gradually increases from week 35 in accordance with the increased contract rate. At week 80 engineers assigned to project teams start to work overtime to carry out the increased orders. Meanwhile management effort toward feedback of know-how continuously declines because of increases in the work load. Eventually, no management effort exists toward feedback of know-how at a period (week 200 thru 255) when the work load reaches more than 1.9. The tremendous overtime work load of 1.9 or more is then exercised in the firm for a little more than one year. It is an interesting pattern that the first peak of the work load is observed during a period when the contract rate and also the number of projects in progress decrease.

This phenomena occurs for the following reasons: By less management effort toward feedback, the know-how level begins to decline at week 110. Meanwhile the expected know-how level by the general customers increases, producing a larger gap of the know-how level between the firm and the customers. This gap directly affects the project teams' performance. For instance, by rough process engineering, a lot of revision work of plant engineering and detailed engineering occurs, causing confusion in procurement and field construction work. The firm's engineers waste a great amount of their time on the revision work to meet the customer's expectation.

Although the firm's engineers put forth their efforts to solve those difficulties, the customers are not usually satisfied by the firm's accomplishment under the existing gap of the know-how level. It influences the contract rate by means of a decrease in the competitiveness. Therefore, the firm experiences contradiction such that the work load increases even though the contract rate decreases during a period (week 110 thru 220) and the number of engineers gradually increases.

The know-how level, which starts to drop at week 110, is below the customers' expected level at week 135, causing an increase in the work load as mentioned above. During a period (week 135 to week 395) the know-how level is below the customers' expected level. As a result, the contract rate falls to 0.9.

The competitiveness, which reaches the first peak at week 30, decreases while the know-how level is below the customers' expected level and falls to a low at week 245. The firm faces an operational crisis due to the low competitiveness which continues for about 90 weeks (week 245 thru 330).

At week 325 the number of contracts in progress drops to a minimum of 24, while the number of idle engineers increases. The firm's management starts to put forth its effort toward feedback of know-how about one year before this, and continues at rather rapid rate of an increase in its effort. Although management effort reaches the second peak at week 380, it takes about two more years to reach a peak of the know-how level, which implies a difficulty in feedback of know-how. During a period (week 350 thru 440) the firm's president and some directors directly participate and establish a temporary system to carry out immediate feedback of know-how, so that almost all engineering managers naturally join feedback effort in various ways. The small work load during the period makes this effort possible. At week 330 to week 520 no overtime on an average exists. By this strong effort engineering know-how, which has accumulated in the individual engineer's brains or filing cabinets for the past four years, is systematically reviewed and compiled. The know-how level then starts to raise.

As the strong management effort was adopted it has inertia, and it slowly decreases. After the know-how level reaches the customers' expected level at week 400, however, management effort toward feedback starts to drop. In accordance with the know-how level raised, the competitiveness increases, causing an increase in the contract rate. By increasing the work load again, management effort toward feedback gradually decreases until the end of the simulation time (week 520). Therefore, development of the know-how decays after it reaches the second peak at week 475, while the customers' expected level is raising. It causes a decrease in the competitiveness and the contract rate starts to drop again at week 500. Although the number of contracts in progress reaches the second peak of 150 at week 505, the work load does not increase as much. This is because the know-how level is higher than the customers expected level. In other words, various engineering work, procurement and field construction are effectively carried out on the basis of up-to-date know-how.

The pattern at the end of the simulation suggests that the firm will experience the same situation as it had from around week 100.

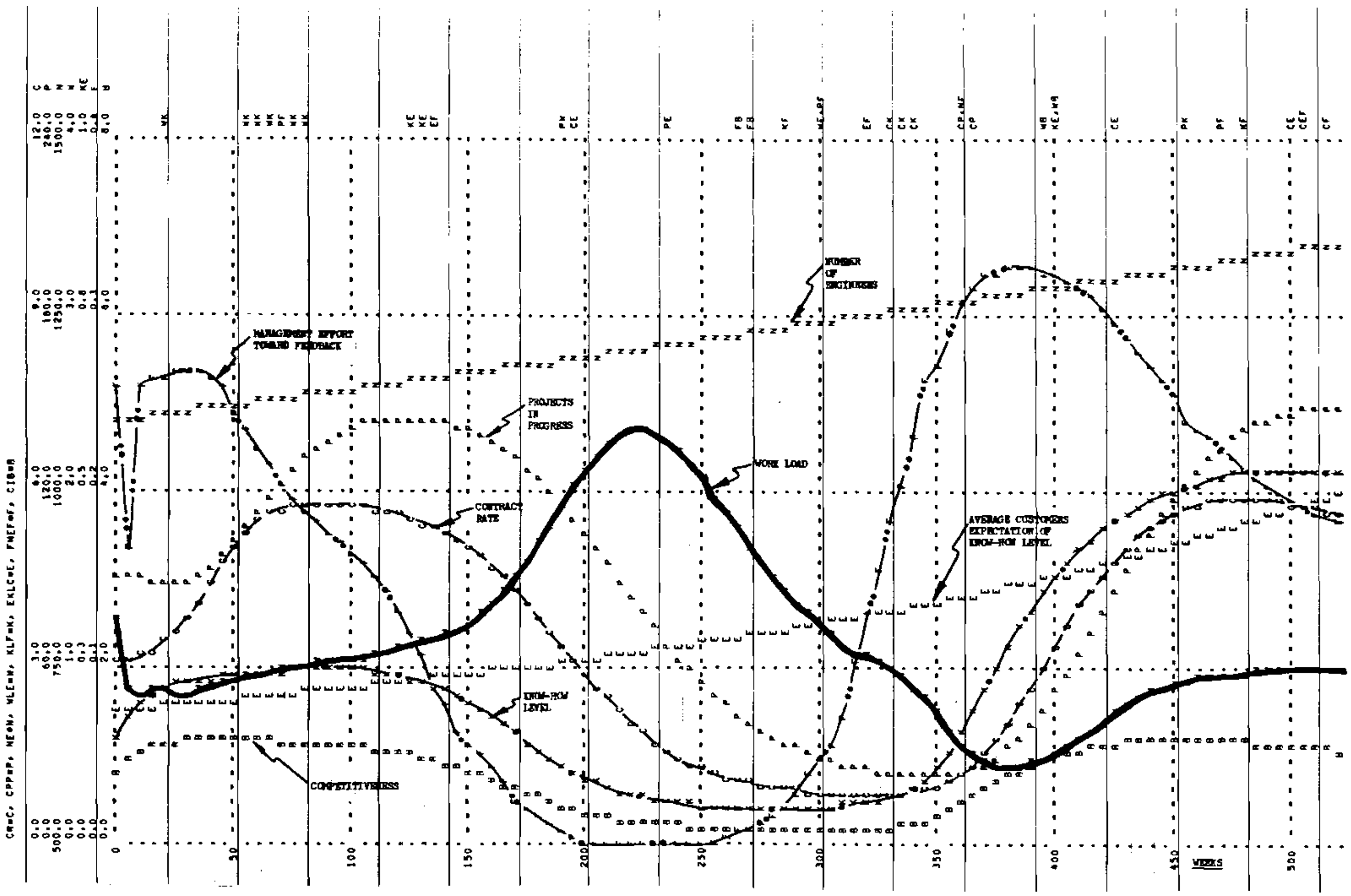


Figure 14. Run #1

The model behavior as shown in Figure 14 is a reasonable representation of actual system performance. The first run demonstrates how the firm's policies interact with the customers' expected know-how level to create a highly fluctuating work load. Significant improvement in stability may be obtained by changing some of the firm's policy structure and/or parameters.

System Behavior with Changes in Parameters

Delay in Know-How Obsolescence Lengthened (Run 2)

Loop A and B in Figure 3 show how the know-how level influences the firm's operation. The know-how level varies with management effort toward feedback of know-how. When management effort is high, the know-how level raises, increasing the competitiveness and decreasing the work load.

The model is tested for a change in the value on the delay in know-how obsolescence DKHO. The new value of the delay is 19 weeks which is one and one half months longer than the original delay. This is a hypothetical model, and it is assumed that it is possible to lengthen the delay in know-how obsolescence without changing the basic model.

Figure 15 shows the behavior of the model for a 25 per cent step input with the change in the delay. The model is otherwise identical to the basic model.

Soon after the simulation starts, the know-how level rapidly increases, and reaches the first peak of 0.40 at week 95. Since the know-how level is much higher than the customers' expected level, the competitiveness also increases, causing a rapid increase in the contract rate.

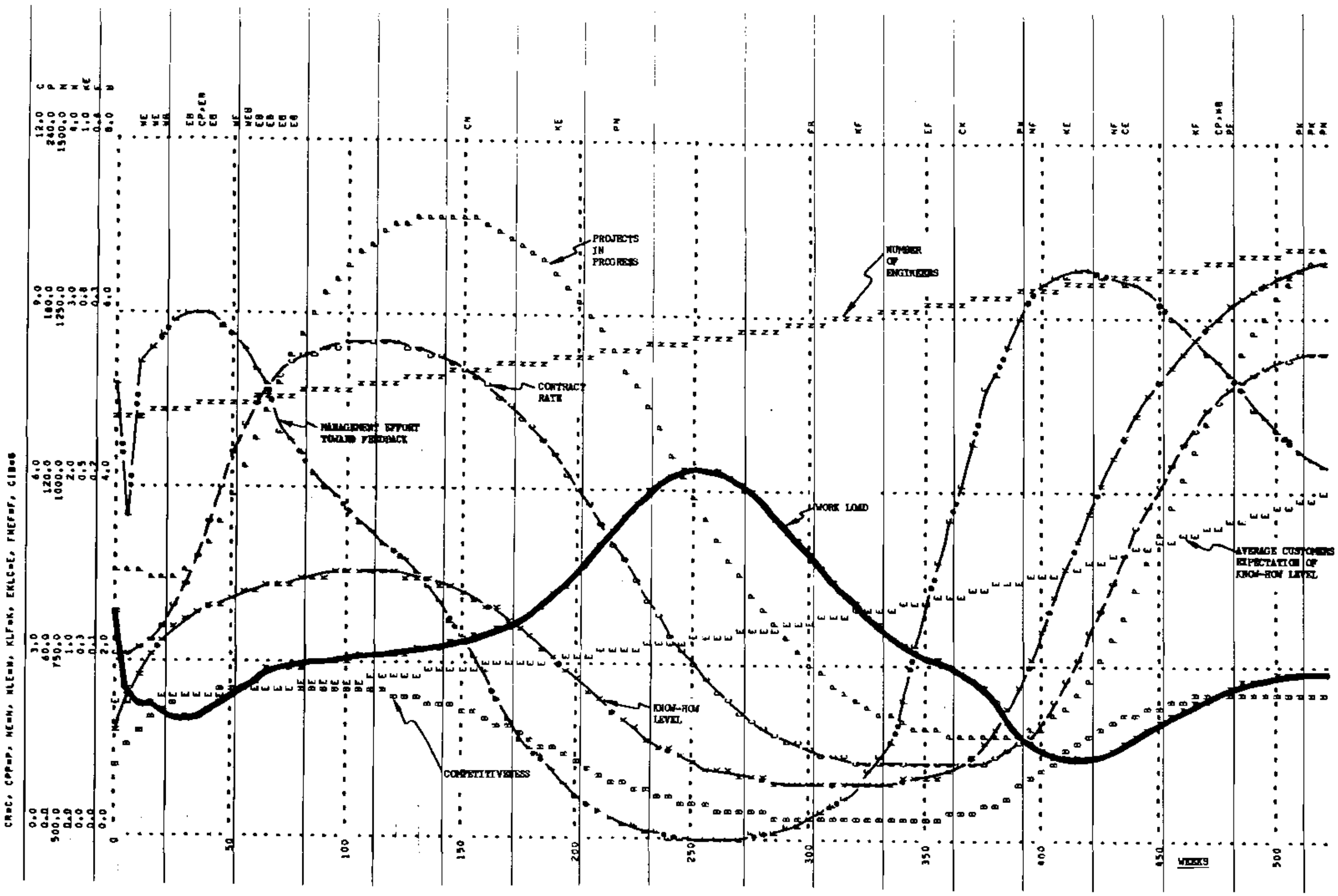


Figure 15. Run #2

At week 100 the contract rate reaches the first peak which is about 50 per cent higher than Run 1. In accordance with the increased work load, management effort toward feedback of know-how decreases and thereafter the firm follows the same pattern as mentioned in the case of Run 1.

It is interesting to note that the number of projects in progress at the peak of the work load is 126 in Run 2, while it is only 84 in Run 1. Furthermore, the peak of the work load in Run 2 is lower than that in Run 1.

A period during which the know-how level is below the customers' expected level is about four years in Run 2, while it is about five years in Run 1.

By putting forth strong management effort toward feedback of know-how from around week 350, the know-how level reaches 0.83 at the end of the simulation (week 520). In an actual case the know-how level might be above what can be expected for the firm. It is useful, however, to demonstrate the effects of the delay in know-how obsolescence on the model behavior in order to help management to realize the importance of keeping know-how up-to-date.

Delay in Feedback of Know-How Lengthened (Run 3)

Another important parameter in the system is the delay for feedback of know-how DFK. It is expected that an increase in this delay will increase the decay of the know-how level.

Figure 16 shows the behavior of the system in response to a 25 per cent input with the change in the delay for feedback of know-how which equals 45 weeks instead of the original value of 39 weeks. The model is otherwise the same as the initial model.

Comparing Run 3 with Run 2, it is observed that the system behavior

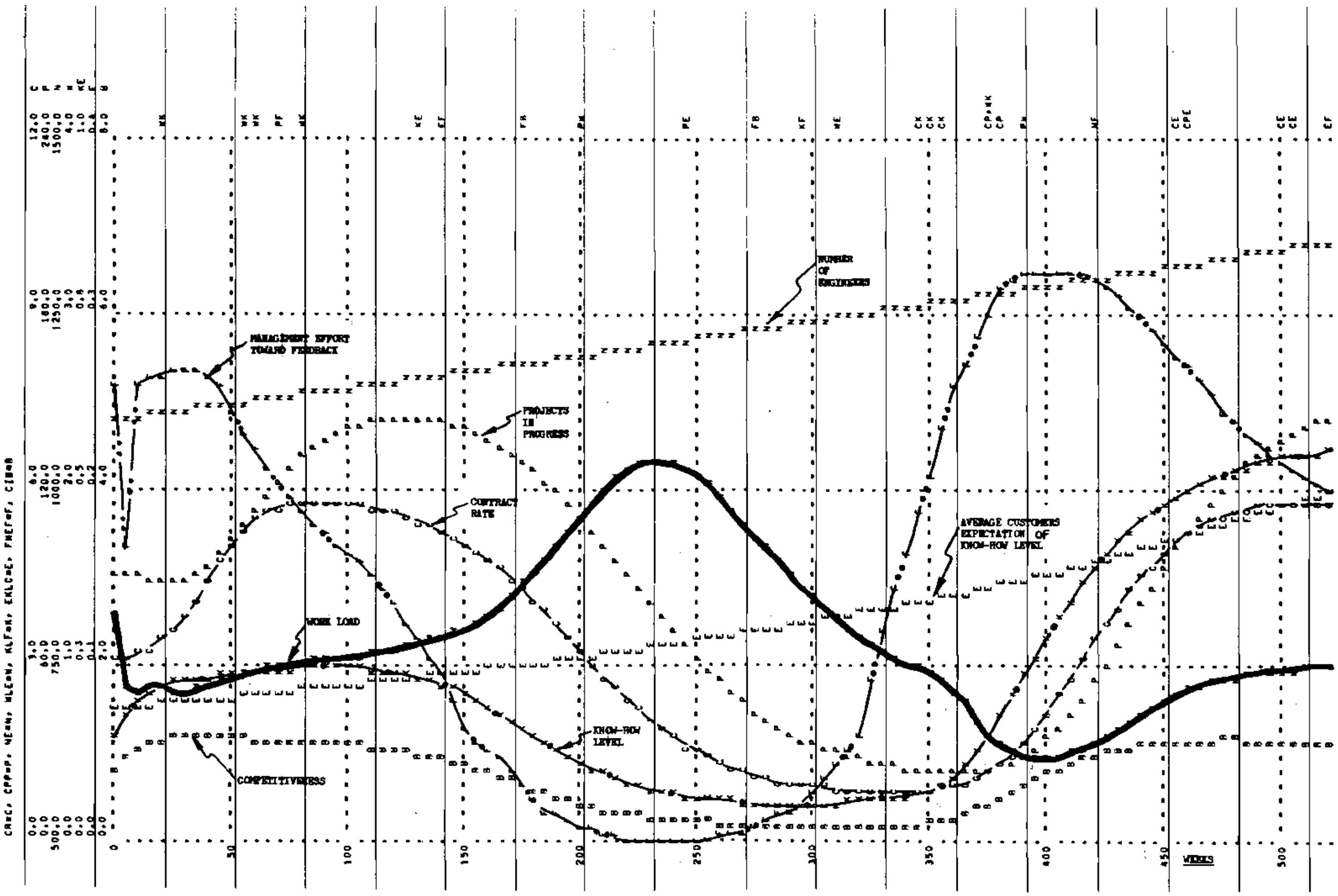


Figure 16. Run #3

of Run 3 indicates the opposite difference from the analytical results of Run 1 and Run 2. In other words, the behavior of Run 3 is very close to Run 1, even though the obsolescence time of know-how (=DFK + DKHO) of Run 3 is the same 58 weeks as Run 2. The delay in know-how obsolescence conspicuously affects the firm's operation. For instance, it can be seen that the longer DFK or shorter DKHO causes a decrease in first the know-how level and then the contract rate.

Although the system behavior of Run 3 is similar to Run 1, some of its behavior characteristics are more desirable. For instance, the peak of the work load is lower, and the second peak of the know-how level at the end of the simulation time is higher than Run 1.

In summary, Runs 2 and 3 show that an increase in the obsolescence time of know-how from 52 weeks to 58 weeks significantly raises the know-how level and reduces the peak of the work load.

CHAPTER VI

IMPROVEMENT OF THE MODEL

The objective dealt within this chapter is to design a new policy which significantly increases the system stability.

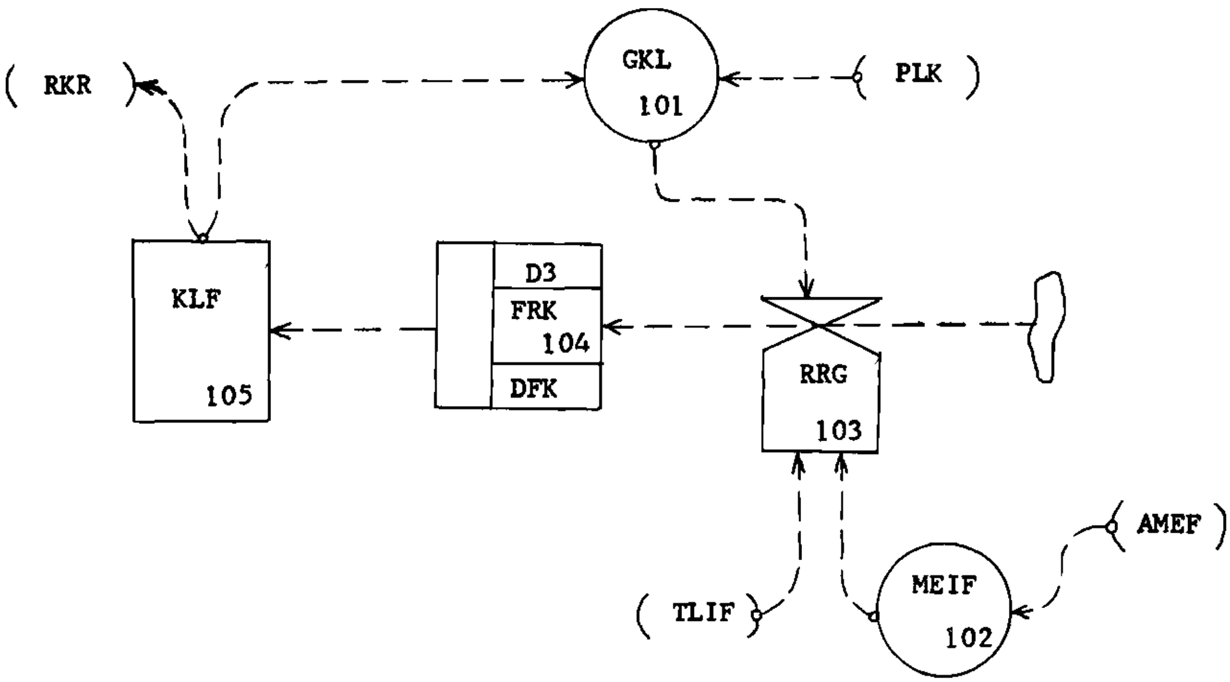
In the basic model the behavior was characterized by fluctuations in the contract rate, the work load, and the know-how level. The problem arose mainly from the firm's policies controlling the know-how level. The feedback activities of know-how in the firm were not stable, causing fluctuations of the know-how level. Therefore, the new policy involves a change in the feedback system of know-how.

Referring to Figure 1, feedback of know-how was carried out mainly from the information at the stage of the completion of projects. The new policy, however, responds to the information at the stage of not only the completion of projects but also the evaluation of projects progress and the loss of contracts.

Formulation of the Improved Model

A flow diagram of the improved model is shown in Figure 17. The recognition of the gap between the firm's know-how level and the potential know-how level is more effective under the new policy. Even the recognition of the up-to-date know-how level in the firm itself is difficult under the original policy.

First, the gap between the firm's and the potential know-how level



PLK	....	Potential Level of Know-How (dimensionless)
GKL	....	Gap between the Firm's and the Potential Know-How Level (dimensionless)
RRG	....	Recognition Rate of the Gap (dimensionless)
MEIF	....	Management Effort Influence on Feedback (1/week)
TLIF	....	Trained Level Influence on Feedback (dimensionless)
FRK	....	Feedback Rate of Know-How (1/week)
DFK	....	Delay in Feedback of Know-How (weeks)
KLF	....	Know-How Level by Feedback (dimensionless)
RKR	....	Relative Know-How Ratio between the Firm and the Customers (dimensionless)
AMEF	....	Average Management Effort toward Feedback (managerial time/week)

Figure 17. A Flow Diagram of New Feedback Policy

is formulated.

$$GKL.K = PLK.K - KLF.K \qquad 101,A$$

GKL .... Gap between the Firm's and the Potential Know-How Level (dimensionless)
PLK .... Potential Level of Know-How (dimensionless)
KLF .... Know-How Level by Feedback (dimensionless)

Next is an equation for management effort influence on feedback of know-how. Although the new system is adopted in the firm, feedback of know-how still depends strongly on management effort. There exists different estimates for effectiveness of management effort toward feedback of know-how. Figure 18 shows these estimates of the influence of management effort. The pattern will be estimated as the same pattern as in the basic model. Later, the model will be tested for sensitivity of the parameters. The results of the test would also be useful to improve the new system. In other words, the new system should work to be able to acquire the amount of know-how which is illustrated in Figure 18.

$$MEIF.K = TABHL\ (TBMEF,\ AMEF.K,\ 0,\ 1600,\ 200) \qquad 102,A$$

$$TBMEF^{*} = -.25/-.20/-.075/.225/.425/.500/.550/.585/.600$$

MEIF .... Management Effort Influence on Feedback (1/week)
AMEF .... Average Management Effort toward Feedback (managerial time/week)
TBMEF .... Table for MEIF (see Figure 18)

The above equation assumes accurate estimates of the influence in responding to management effort.

The recognition rate of the gap between the firm's know-how level and the potential know-how level is set equal to the gap modified by the trained level and management effort influence on feedback of know-how.

$$RRG.KL = (TLIF.K)(MEIF.K)(GKL.K) \qquad 103,R$$

RRG .... Recognition Rate of the Gap (1/week)
TLIF .... Trained Level Influence on Feedback (dimensionless)

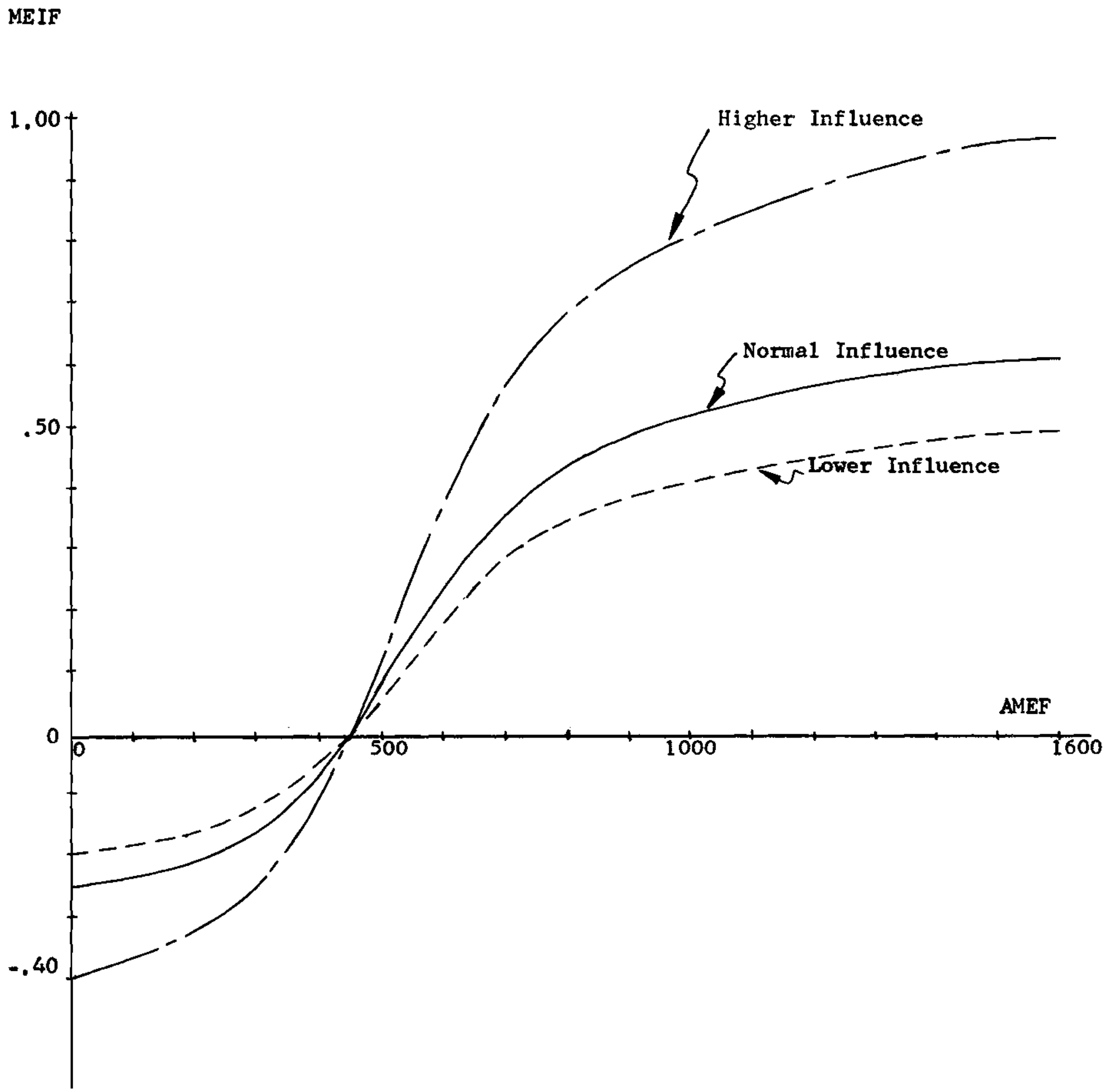


Figure 18. Management Effort Influencing Know-How Level vs. Average Management Effort

MEIF .... Management Effort Influence on Feedback (1/week)
GKL .... Gap between the Firm's and the Potential Know-How Level (dimensionless)

After the recognition of existence of new know-how or needs of revising know-how, several months are necessary for discussing, compiling, printing, distribution and understanding new know-how. The delay in feedback of know-how is assumed to be 20 weeks. Under the new system, feedback of know-how can be continuously carried out. Therefore, the delay of discussing and compiling becomes shorter than the basic model.

FRK.KL = DELAY 3(RRG.JK, DFK) 104,R

DFK = 20

FRK .... Feedback Rate of Know-How (1/week)
RRG .... Recognition Rate of the Gap (1/week)
DFK .... Delay in Feedback of Know-How (weeks)

The know-how level is formulated as a regular level equation.

KLF.K = KLF.J + (DT)(FRK.JK + 0) 105,L

KLF = .15 105,N

KLF .... Know-How Level by Feedback (dimensionless)
FRK .... Feedback Rate of Know-How (1/week)

The change in the policy is now completed.

Analysis of the Improved Model

On the basis of the new management policy, the behavior of the model is now simulated. The improved model is exactly like the basic model except for changes in the feedback policy of know-how. First the model is tested with a step input as in Run 4. Then the sensitivity of the system behavior is examined by changing a parameter of management effort influence on feedback of know-how as in Runs 5 and 6.

Behavioral Analysis for the Step Input (Run 4)

Looking at the model behavior shown in Figure 19, it can be seen that the behavioral patterns are greatly changed and improved. The old policy creates a highly oscillatory system, while the new policy creates a damped system.

The 25 per cent step increase in prospective bids occurs at the same week 26 as the original model, and afterwards the contract rate rises. The number of engineers and the customer's expected know-how level are also exactly the same as the original model.

Comparing with Run 1, it can be observed in more detail how the new policy improves the system behavior. At week 150 the firm's know-how level is higher than the customer's expected level. This occurs as early as week 10 in Run 1. The system in Run 1 has the stronger competitiveness during the first three years of the simulation time. Because of the increase in the know-how level, the contract rate in the improved model equals the contract rate of Run 1 at week 150. This implies that management under the new policy keeps its effort toward feedback of know-how rather stable while controlling the contract rate. Meanwhile the old policy tends to carry out immediate feedback of know-how when some engineers are idle. When the contract rate is great, management under the old policy puts forth its effort to handle as many orders as possible while reducing its effort toward feedback of know-how. At week 185 the contract rate in Run 4 reaches 5.2 contract per week, and subsequently keeps stable. The number of projects in progress also reaches the stable level of 134 at week 225.

The fluctuations of the work load is drastically improved. Engineers are now free from the tremendous overtime work. They are now able

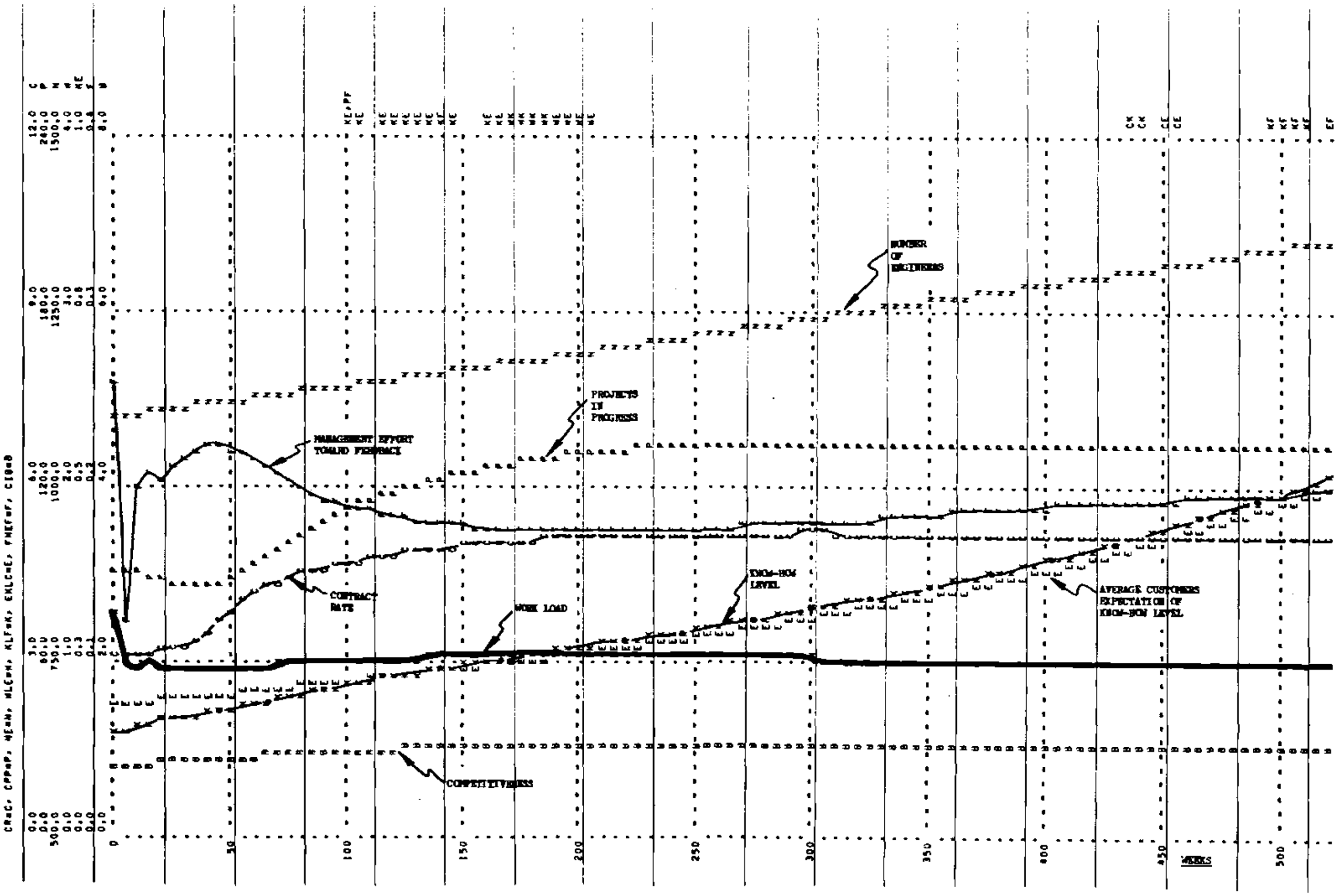


Figure 19. Run #4

to attend various training courses and also pursue the current literature in their fields. Thus, the potential ability of the engineers raises keeping the high know-how level. On the other hand, although the number of engineers steadily increases through the simulation, no idle engineers exist from week 70. According to a rather rapid increase in the customers' expected know-how level with the passing of the simulation time, the complexity of the projects increases, causing an increase in the work load.

In order to keep a higher know-how level than the customers' expected level, management effort toward feedback of know-how under the new policy reaches a peak of 22.4 per cent at week 40, but later it gradually declines. After it reaches a low of 17.5 per cent at week 105, however, management effort grows up to the steady-state condition. In accordance with overtaking the increase in the customers' expected level as mentioned above, from then, management effort toward feedback of know-how steadily increases.

System Behavior with Changes in a Parameter

Having dealt with the behavior of the system for the new policy, the policy is tested for a range of values for a parameter, which is a table value for management effort influencing the know-how level (see Equation 102,A and Figure 18). The behavior is examined for the lower influence (Run 5) and higher influence (Run 6) in estimates of the parameter. Although management does not have knowledge of the exact influence of the parameter value, the model behavior needs to be insensitive to a reasonable range of the parameter.

Figure 20 shows the result of Run 5. As the lower influence of management effort is estimated, the know-how level is below the customers' expected level through the simulation. Comparing with Run 4, it is observed that the stabilized peak of the contract rate is 9.5 per cent lower than Run 4. The work load is, however, very stable, and the behavior is identical to Run 4. Therefore, the work load is not sensitive to the lower parameter value.

Figure 21 depicts the result of Run 6. The know-how level exceeds the customers' expected level at week 60, and subsequently stays higher than the customers' expected level. In accordance with the high level of know-how, the contract rate increases for the first five years. After the contract rate reaches a peak of 6.5, it begins to decrease at week 385. The increasing rate of the customers' expected level of know-how influences this decrease in the contract rate. Comparing with Run 4 again, it is observed that the behavior of the work load is like Run 4, even though the contract rate increases 25 per cent over Run 4 at the peak. Therefore, the work load fluctuations of Run 6 are not sensitive to the higher parameter value.

Although there exists some fluctuations of management effort toward feedback of know-how during the first five years among Runs 4, 5 and 6, these fluctuations tend to stabilize in the long run. Thus, the new policy has significantly improved the model behavior. By adopting the new policy, management has created a system that is insensitive to the exact parameter value of management effort influencing the know-how level.

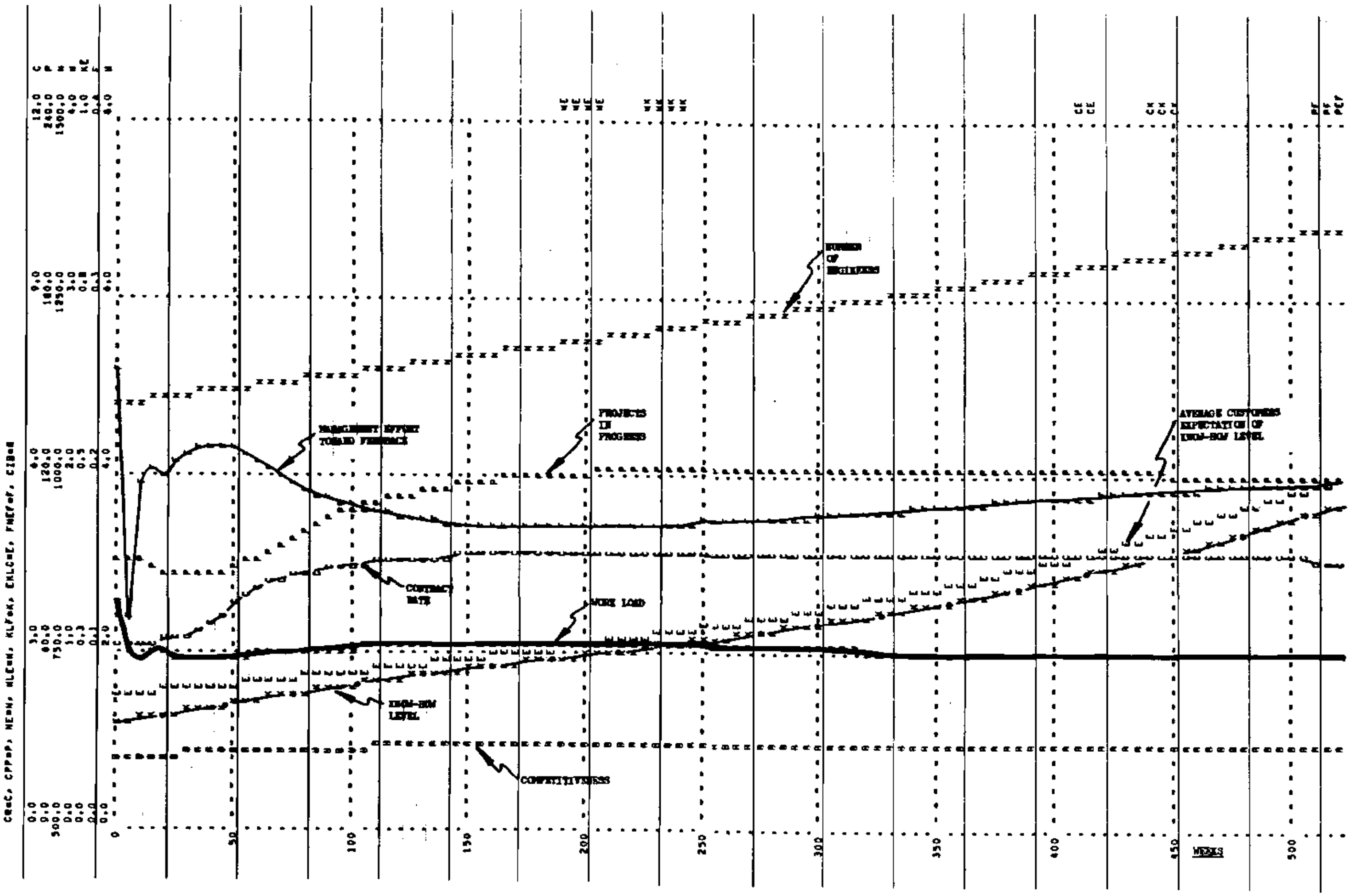


Figure 20. Run #5

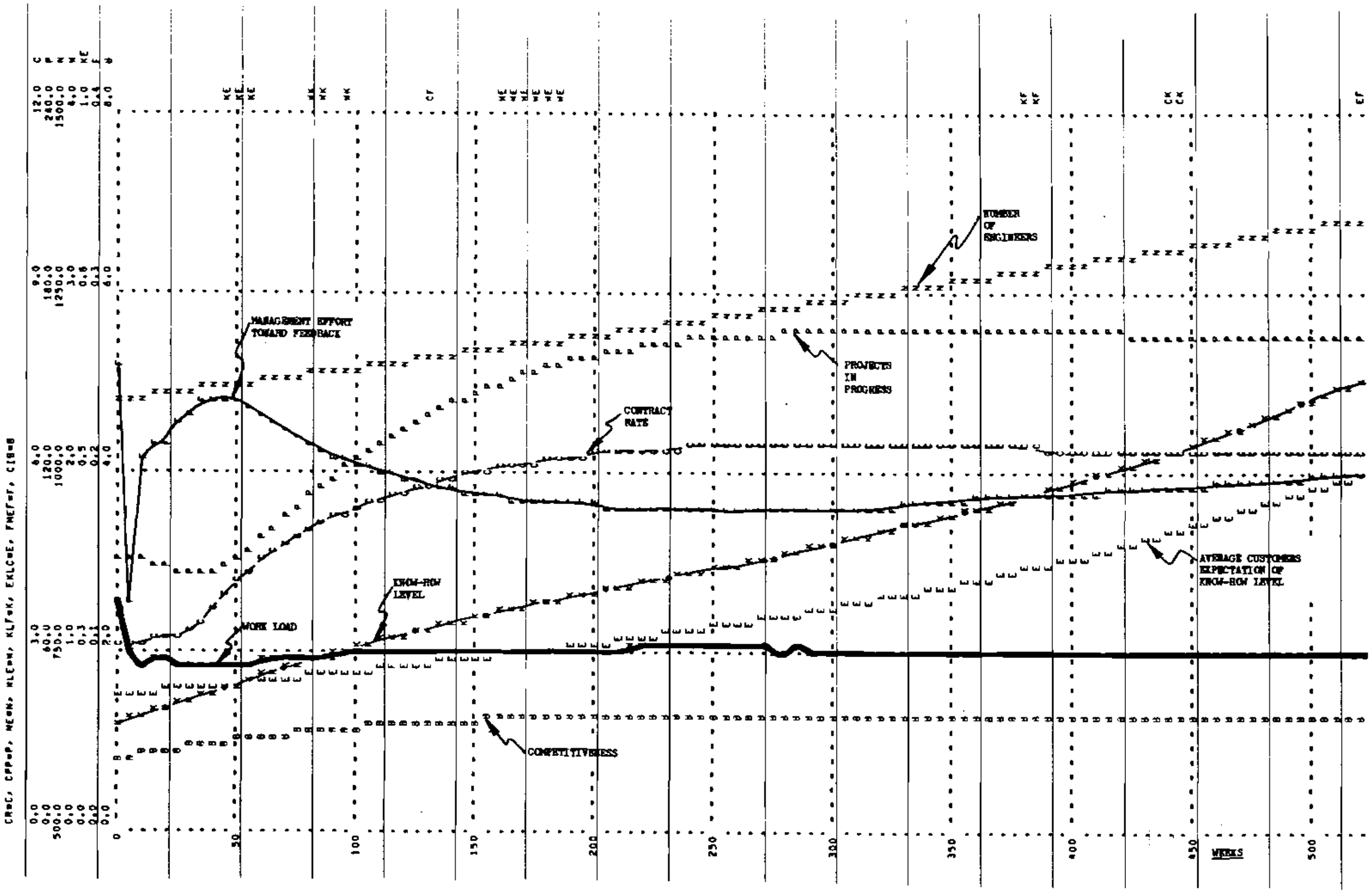


Figure 21. Run #6

CHAPTER VII

CONCLUSIONS

The use of simulation does not eliminate the need for trial programs, but it does provide a basis for weeding out grossly infeasible ideas before trial. At present a manager in the engineering organization must believe either his own judgment about the system, the judgment of those who want to sell the system, or that of other managers who have successfully used such systems in other organizations, even though he may feel that the salesman is heavily biased and really does not understand his manager's problems, and that other managers who successfully used such systems really had different problems. The use of simulation, however, could provide the manager with some of the experience he needs to make a decision.

By means of the simulation experiments described in Chapters III through VI, the key influences upon the engineering organization success and failure have been isolated and studied in depth. The factors of consequence emerging from these studies can be conveniently grouped into two categories:

1. Management policies influencing the engineering know-how level and the work load for engineers.
2. Characteristics relating to the number of orders.

First, problems of management policies, of which existence has been recognized by managers in the engineering organization but could not be solved sufficiently, have been better defined by using the philosophy and methodology of Industrial Dynamics. That is to say, objectives of management, which should be a basis to build management policies, could be provided by the analysis of the systems behavior of the original and improved model described in Chapters V and VI. By changing the feedback system structure of engineering know-how, large improvement of the systems behavior in terms of the steadily increasing know-how level and the stable work load was acquired.

Second, the order characteristics have been investigated at the same time. There is no doubt that the competitiveness of an engineering organization strongly affects the number of incoming orders. The know-how level directly influences the competitiveness. Therefore, the improved model has demonstrated the stable competitiveness while maintaining a stable number of orders due to the steadily increasing know-how level, even though the customers' expected know-how level to the engineering organization had increased.

The results of this study should help managers to note an important objective of management for an engineering organization. This has suggested the possibility of experiments to management policy influence on the total system of an engineering organization.

CHAPTER VIII

RECOMMENDATIONS

The application of the philosophy and methodology of Industrial Dynamics to the problems of engineering organization management has hopefully strengthened an understanding of the field. It seems worthwhile to outline extensions of the study, amenable to the same approach, which are potential contributions to an even superior recognition of the determinant factors of project life cycles.

A possible extension of the model is the introduction of the growth of the chemical industry. Although this study has developed the ideal fluctuations of the work load for engineers, a stable number of orders is not a favorable situation. In order to respond to the increasing wages due to the increased number of engineers, the number of orders should increase steadily. Consequently, if the growth of the chemical industry is introduced in the model, the number of orders would increase as long as the engineering organization remains competitive while the market extends. The model could then be more realistically presented.

Another useful extension would visibly demonstrate the important relationships of the money flow in terms of the profits in the engineering organization. The high know-how level should increase engineering productivity causing an increase in the profits. In a similar manner the increased profits can release the operational pressure of the organization caused by the increased wages, even though the number of orders does not increase. Due to this extension the model investigated will more readily approach the real world situation.

APPENDIX A

```
RUN

      AN INDUSTRIAL DYNAMICS STUDY BY S. TAKAHASHI

      A DYNAMIC ANALYSIS OF AN ENGINEERING ORGANIZATION  (A BASIC MODEL)

      CONTRACT PROCESSING SECTOR

18R   PB.KL=(CTB.K)(PBNC+TEST.K)                  PROSPECTIVE BIDS          ST0001
45A   TEST.K=STEP(1,26)                           TEST INPUT                ST0002
39R   CR.KL=DELAY3(PB.JK,DCR)                     CONTRACT RATE             ST0003
1L    COPT.K=COPT.J+(DT)(CR.JK-POR.JK)            CONTRACTS IN ORGANIZIN    ST0004
20R   POR.KL=COPT.K/DOPT                          PROJECT ORGANIZE RATE     ST0005
1L    CPP.K=CPP.J+(DT)(POR.JK-CCR.JK)             CONTRACT IN PROGRESS      ST0006
20R   CCR.KL=CPP.K/DCP                            CONTRACT COMPLETE RATE    ST0007
20A   CTB.K=1/RKR.K                               COMPETITIVENESS           ST0008

      ENGINEERS ACQUISITION SECTOR

12R   EHR.KL=(EINE)(NE.K)                         ENGR HIRING RATE          ST0009
12R   ELR.KL=(EONE)(NE.K)                         ENGR LEAVING RATE         ST0010
39R   NTE.KL=DELAY3(EHR.JK,DTE)                   NEWLY TRAINED ENGINEER    ST0011
1L    NET.K=NET.J+(DT)(EHR.JK-NTE.JK)             NO OF ENGR IN TRAINING    ST0012
1L    TE.K=TE.J+(DT)(NTE.JK-ELR.JK)               TRAINED ENGINEER          ST0013
7A    NE.K=TE.K+NET.K                             NO OF ENGINEERS           ST0014
12A   NEAP.K=(PAE.K)(NE.K)                        NO OF ENGR FOR ASSIGN     ST0015
58A   MEIN.K=TABHL(TBMEN,AMEF.K,0,1600,200)       MGT EFFORT INFL ON EDR    ST0016
12A   PAE.K=(NPNE)(MEIN.K)                        PERCENT OF ASSIGN ENGR    ST0017

      WORK LOAD DETERMINATION SECTOR

12R   EAR.KL=(NENC)(POR.JK)                       ENGR ASSIGNING RATE       ST0018
12R   ERR.KL=(NENC)(CCR.JK)                       ENGR RELEASING RATE       ST0019
1L    NEOP.K=NEOP.J+(DT)(EAR.JK-ERR.JK)           NO OF ENGR OCCUPIED       ST0020
44A   WLE.K=(RKR.K)(NEOP.K)/NEAP.K                WORK LOAD FOR ENGR        ST0021

      MANAGEMENT EFFORT SECTOR

3L    AWLE.K=AWLE.J+(DT)(1/DAWLE)(WLE.J-AWLE.J)   AVE WORK LOAD FOR ENGR    ST0022
58A   FMEF.K=TABHL(TBFME,AWLE.K,0,3,0.3)          FR OF MGT EFFORT TO FB    ST0023
12A   MEF.K=(MT)(FMEF.K)                          MGT EFFORT TO FEEDBACK    ST0024
3L    AMEF.K=AMEF.J+(DT)(1/DAMEF)(MEF.J-AMEF.J)   AVE MGT EFFORT            ST0025

      ENGINEERING KNOW-HOW SECTOR

58A   PLK.K=TABHL(TBPLK,TIME.K,0,520,40)          POTENTIAL KNOW-HOW        ST0026
58A   MEIF.K=TABHL(TBMEF,AMEF.K,0,1600,200)       MGT EFFORT INFLUENCE      ST0027
20A   TRLE.K=TE.K/NE.K                            TRAINED LEVEL OF ENGR     ST0028
3L    STLE.K=STLE.J+(DT)(1/DCTL)(TRLE.J-STLE.J)   SMOOTHED TRAINED LEVEL    ST0029
58A   TLIF.K=TABHL(TBTLF,STLE.K,0,1.0,0.2)        TRAIN LEVL INFL ON EDR    ST0030
13R   ARK.KL=(PLK.K)(TLIF.K)(MEIF.K)              ACQUISITION RATE OF KNO   ST0031
39R   FRK.KL=DELAY3(ARK.JK,DFK)                   FEEDBACK RATE             ST0032
20R   ORK.KL=KLF.K/DKHO                           OBSOLESCENCE RATE         ST0033
1L    KLF.K=KLF.J+(DT)(FRK.JK-ORK.JK)             KNOW-HOW LEVEL            ST0034
12A   EKLC.K=(CRNC)(PLK.K)                        EXPECTED KNOW-HOW LEVEL   ST0035
20A   RKR.K=EKLC.K/KLF.K                          RELATIVE KNOW-HOW RATIO   ST0036
```

Figure 22. Card Listing

```
       INITIAL CONDITIONS

6N     TEST=0
6N     COPT=10
6N     CPP=90
6N     MET=150
6N     TF=950
6N     MEOP=540
6N     AWLE=.89
6N     AMFF=MFF
6N     STLE=TRLF
6N     KLF=.15

       CONSTANTS

C      PRNC=4        CONTRACTS/WEEK
C      DCR=26        WKS
C      DOPT=2        WKS
C      DCP=26        WKS
C      FINF=.0010    NO DIM
C      FONF=.0006    NO DIM
C      DTF=156       WKS
C      NPNF=.70      NO DIM
C      MENC=6        MEN/CONT
C      DAWLE=4       WKS
C      MT=3800       TIME/WK
C      DAMFF=4       WKS
C      DCTL=4        WKS
C      DEK=32        WKS
C      DKHO=13       WKS
C      CRNC=.50      NO DIM
C      TRMFN*=1.03/1.01/.98/.94/.82/.70/.66/.64/.62
C      TRFME*=.35/.340/.315/.26/.06/.02/.008/0/0/0/0
C      TRPLK*=.38/.40/.43/.46/.49/.52/.56/.60/.65/.70/.76/.83/.91/1.00
C      TRMFF*=.10/.14/.24/.48/.64/.70/.74/.76/.78
C      TRTLF*=.02/.035/.05/.06/.07/.08/.087/.093/.10/.11/.13

       OUTPUT FORMAT

PLOT   CR=C(0,12.0)/CPP=P(0,240)/NF=N(500,1500)/WLE=W(0,4.0)/KLF=K,EKLC=F
X1     (0,1.00)/FMFF=F/CTR=R(0,8.0)
SPEC   DT=1/LENGTH=520/PRTPER=10/PLTPER=5
```

Figure 22. Card Listing (continued)

APPENDIX B

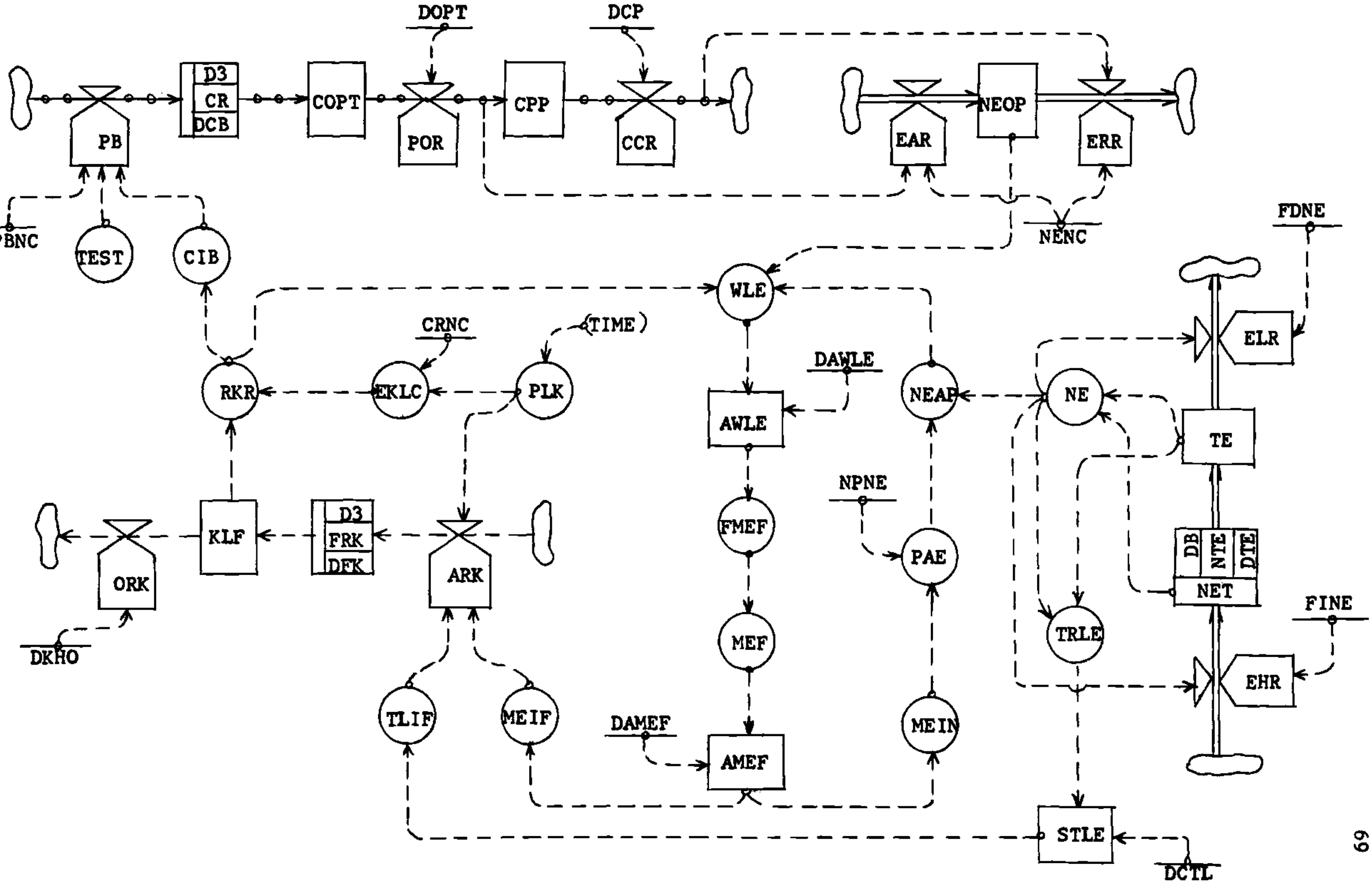


Figure 23. Complete Flow Diagram

APPENDIX C

Glossary of Identifiers

The identifiers of all variables used in the model are listed in alphabetical order. The variable type is given in the column of the equation number using the following symbols:

L .... Level

R .... Rate

A .... Auxiliary

C .... Constant

S .... Supplementary

Variable Name	Variable Defined in Figure	Variable Defined in Equation
AMEF	5, 8, 10, 17	25 - L
ARK	10	31 - R
AWLE	8	22 - L
CCR	4, 7	7 - R
CIB	4	8 - A
COPT	4	4 - L
CPP	4	6 - L
CR	4	3 - R
CRNC	10	C
DAMEF	8	C
DAWLE	8	C
DCB	4	C

APPENDIX C (Continued)

Variable Name	Variable Defined in Figure	Variable Defined in Equation
DCP	4	C
DCTL	10	C
DFK	10, 17	C
DKHO	10	C
DOPT	4	C
DTE	5	C
EAR	7	18 - R
EHR	5	9 - R
EKLE	10	35 - A
ELR	5	10 - R
ERR	7	19 - R
FDNE	5	C
FINE	5	C
FMEF	8	23 - A
FRK	10, 17	32 - R, 104 - R
GKL	17	101 - A
KLF	10, 17	34 - L, 105 - L
MEF	8	24 - A
MEIF	10, 17	27 - A, 102 - A
MEIN	5	16 - A
MT	8	C
NE	5, 10	14 - A
NEAP	5, 7	15 - A
NENC	7	C

APPENDIX C (Continued)

Variable Name	Variable Defined in Figure	Variable Defined in Equation
NEOP	7	20 - L
NET	5	12 - L
NPNE	5	C
NTE	5	11 - R
ORK	10	33 - R
PAE	5	17 - A
PB	4	1 - L
PBNC	4	C
PLK	10, 17	26 - A
POR	4, 7	5 - R
RKR	4, 7, 10, 17	36 - A
RRG	17	103 - R
STLE	10	29 - L
TBFME	9	C
TBMEF	12, 18	C
TBMEN	6	C
TBPLK	11	C
TBTLF	13	C
TE	5, 10	13 - L
TEST	4	2 - A
TLIF	10, 17	30 - A
TRLE	10	28 - A
WLE	7, 8	21 - A

BIBLIOGRAPHY

1. Archibald, R. D., and Villoria, R. L., Network-Based Management Systems, (PERT/CPM), John Wiley & Sons, Inc., New York, 1967.

2. Chu, K., and Naylor, T. H., "A Dynamic Model of the Firm," Management Science, May, 1965, pp. 736-750.

3. Clark, Thomas B., "The System Dynamics of Product Development Control," M. S. Thesis, Georgia Institute of Technology, 1968.

4. Dearden, John, "How to Organize Information Systems," Harvard Business Review, March - April, 1965, pp. 65-73.

5. Donald, A. G., Management, Information and Systems, Pergamon Press, New York, 1967.

6. Forrester, Jay W., Industrial Dynamics, The M. I. T. Press, Cambridge, Massachusetts, 1961.

7. Forrester, Jay W., "Industrial Dynamics: A Major Breakthrough for Decision Makers," Harvard Business Review, July - August, 1958, pp. 37-66.

8. Fuller, Don, Organizing, Planning and Scheduling for Engineering Operations, Farnsworth Press, Boston, Massachusetts, 1964.

9. Karger, D. W., and Murdick, G., Managing Engineering and Research, The Industrial Press, New York, 1963.

10. Knight, John E., "A Systems Perspective on Production-Quality-Sales Interface," M. S. Thesis, Georgia Institute of Technology, 1968.

11. Malcolm, Donald G., "System Simulation - A Fundamental Tool for Industrial Engineering," The Journal of Industrial Engineering, May - June, 1958, pp. 177-187.

12. Moravec, Adolph F., "Using Simulation to Design a Management Information System," Management Services, May - June, 1966, pp. 50-58.

13. Naylor, H., Balintfy, L., Burdick, S., and Chu, K., Computer Simulation Techniques, John Wiley & Sons, Inc., New York, 1966.

14. Nord, Ole C., The Problem of Work Load Fluctuations at the Precision Company, Industrial Dynamics Research Memo, (an unpublished memo), October, 1963.

15. Pugh, Alexander L., III, DYNAMO User's Manual, The M. I. T. Press, Cambridge, Massachusetts, 1961.

16. Rase, H. F., and Barrow, M. H., Project Engineering of Process Plants, John Wiley & Sons, Inc., New York, 1957.

17. Roberts, Edward B., The Dynamics of Research and Development, Harper & Row, New York, 1964.

18. Roberts, Edward B., "Industrial Dynamics and the Design of Management Control Systems," Management Technology, Dec. 1962, pp. 100-118.

19. Steinmetz, Lawrence L., "Management by Objectives: How It Works," Hydrocarbon Processing, September, 1967, pp. 193-195.

20. Swanson, Carl V., Some Property of Feedback Systems as a Guide to the Analysis of Complex Simulation Models, Proceedings of the Department of Defense, Logistics Research Conference, Warrenton, Virginia, 1965.